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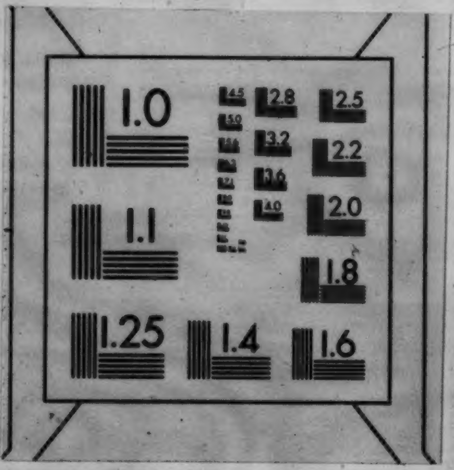
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THE UNIVERSITY OF ALBERTA

Learning and Organization: Some Tracking Studies

by

© Ian Michael Franks

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF Doctor of Philosophy

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THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Learning and Organization: Some Tracking Studies submitted by Ian Michael Franks in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Physical Education.

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Date July 15th 1980

ABSTRACT

A series of tracking studies were completed in order to investigate the processes that underlie the organization and learning of a complex movement sequence. Experiments I and II examined the relationship between two principle performance measures. The within-subject variance score was used as an index of performance consistency, while the cross-correlation function was used to indicate the temporal adjustments in the performance. Both of these measures reflected the improvement in tracking performance during task acquisition. The third and fourth experiments were designed to gain a more complete understanding of the consistency measure used. While Experiment III was concerned with the locus of variability throughout a single movement of a sequence, the fourth experiment compared the consistency index (within-subject variability) with an error measurement (root mean squared error).

An input blanking methodology was used in Experiment V and VI. During these experiments the subjects produced a movement sequence without the aid of any visual display markers. The response that was produced from memory was anlayzed by a Fourier technique. This harmonic analysis yielded information with respect to the amplitude, phasing and frequency of the harmonic components of the response waveform. The results from these two experiments are discussed in the light of recent studies by Glencross (1979) that have proposed a process orientated view of response organization.

Acknowledgments

My sincere appreciation goes to Dr. R. B. Wilberg without whose help and guidance this research would not have been possible. As an advisor and friend he was ambitious for his student. My thanks go to the remaining committee members who showed interest in my research and offered helpful suggestions as to its eventual course. A further note of thanks goes to my external examiner, Dr. J. Higgins and his wife Susan who were both helpful and academically rigorous in their evaluation of this document.

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The series of studies that are described here are investigations into the changes in performance that occur during the acquisition of a tracking task. It is important to note that these experiments are the first of a series designed to elucidate the processes by which a subject organizes a sequence of movements. The organization of a human operators' input, translation and subsequent output has most effectively been studied using various tracking tasks.[†] These tasks usually involve measuring the subject's continuous response to some preprogrammed stimulus signal. When the stimulus signal is periodic and the subject is exposed to several repeated trials, it is possible for him to use information gained from past experience to improve his performance. This past experience will be in the form of some memorial representation of the perceptual and response processes used on earlier trials. The concept of a memorized control sequence producing a learned response is one that is common to most models of the human operator. The label which is usually given to this process is "pattern generation" (Pew, 1974a; Magdaleno, Jex, & Johnson, 1970). Investigations into the functions of this pattern generator have in the past used a methodology termed "input blanking". During input blanking studies the subject tracks a stimulus signal that is visible on an oscilloscope. At random intervals during any one trial the illumination of the display is decreased and the subject continues to put out his response for a prescribed period of time. Examination of the response records during this "lights out" period allows the processes involved in the subject's generation of a pattern to be investigated.

[†] For a brief review of these tasks see Appendix A.

Input blanking was therefore considered to be a worthwhile method through which the generation of organized movement patterns could be studied.[†] However, three major problems needed to be solved before these studies could begin. First, what type of tracking task would be most compatible with the input blanking paradigm? Second, what response measures should be used to indicate the level of performance achieved by the subjects? And third, what is the relationship between these response measures?

One task that was used in the following experiments was termed a "blind tracking task". The subject followed the stimulus signal but did not have any visual indication of his own response. This task was adopted for several reasons. Firstly, earlier input blanking studies (Magdaleno et al., 1970; Vossius, 1965) displayed both stimulus and response markers during the typical pursuit tracking task. When both display markers were removed during input blanking there was a momentary disturbance of responding. The blind tracking task was expected to decrease the disturbing effect of experimental intervention. Also the start of the input blanking was precued to offset any surprise on behalf of the subject. A further reason why only a stimulus marker was displayed was to prevent the subject from becoming "stimulus-bound". When subjects are involved in a pursuit tracking task that involves both stimulus and response markers, they exhibit high frequency response oscillations around the stimulus. That is, they make many corrective responses with the aim of aligning the two displayed markers. These corrective response frequences are not correlated with the stimulus signal and contribute to the subject's response remnant. Freeing the subject from this problem of fine alignment allows him to concentrate on the information gained from both the stimulus signal and the consequences of his own response to the track, while reducing his response remnant.

[†] See Experiments V and VI.

Experiments I through IV were designed to address the remaining problems of assigned measurement. Only a small number of authors (Fitts, Noble, Bahrick, & Briggs, 1959; Henry, 1974; Lathrop, 1965; Pew & Rupp, 1971; Poulton, 1974) have been concerned with improving our understanding of existing indicants of skillful performance. However, a tentative conclusion that may be drawn from these studies is that the outcome of a motor task, as measured by overall achievement, cannot stand alone as a dependent variable in motor learning experiments. Since the production of a movement involves the interplay of several psychological and physiological subroutines (Miller, Galanter, & Pribram, 1960; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979) during a specified time period, the measurement used to describe motor performance should be both diverse and complete with regard to these complex processes. In the following experiments several response measures were recorded simultaneously. These measures were used to describe the subject's response characteristics at different stages of practice and for various task conditions. The subjects' response was defined using three general headings: (1) consistency of performance; (2) temporal adjustment of performance; and (3) signal composition.

(1) Consistency of Performance

The fact that a subject's response becomes more consistent as a result of practice is a well documented phenomenon. This has been found by many authors using a variety of perceptual motor tasks. For example the work of Glencross (1970, 1973, 1979) suggests that the distinguishing factor between skilled and unskilled performers is the consistency and stability of the movement organization within a particular sequence of activity. This is supported by several experiments in which Glencross utilized a repetitive speed skill (hand cranking) as the motor task. He found skilled subjects were better able to maintain a consistent temporal relationship between principle events in the hand cranking task than were unskilled subjects. In the early stages of skill acquisition inappropriate and extraneous response units were selected, whereas the skilled performer achieved his goal of restructuring the response units into a refined temporal pattern of activity.

The variability of human operator performance during compensatory tracking was studied by Burgett (1970). He found that subjects adopted a consistent "signal processing path" and a more uniform control strategy during learning. In a more applied experimental environment, Lewis (1956) came to similar conclusions with respect to skill acquisition and response consistency. Lewis recorded acceleration and deceleration curves for skilled and unskilled drivers, while subjects maneuvered a motor car around 60° corners. The sum of the area difference between the acceleration curves was taken as an index of lack of consistency. Skilled drivers were found to be more consistent than unskilled drivers.

> . . . it seems likely that the skilled driver will have a pattern of behavior for a given situation which experience has taught him is the best. Thus the skilled driver may show a smoother curve of acceleration and deceleration, and a further attempt may lead to a pattern of activity which resembles the previous curve. (p. 131)

More recently Tyldesley and Whiting (1975) found that intermediate and expert table tennis players achieved a consistency of patterning that could not be bettered. The novice table tennis players however, were characterized by an inability to produce a consistent movement pattern and to replicate consistently the temporal initiation points of the forward stroke. These conclusions were based upon results of cinematrographical analysis.

Further use of cinematography was made by Higgins and Spaeth (1972). They found that a subject who was involved in closed skill performance (dart throwing at a stationary target) exhibited a movement pattern in practice that was tightly distributed within a narrow bandwidth of responding. This would imply that with practice the subject reduces his movement variability at any one point in time during the execution of the response. A response measure that reflected this decrease in variability was used in the following series of experiments. Velocity-time curves for each trial were superimposed and the variance was calculated at specified time periods during the trial. An average variance score was calculated for each testing session and this served to indicate the degree of consistency the subject displayed during acquisition.

(2) Temporal Adjustment of Performance

Decisions that are made during a pursuit tracking task involve the subject in prediction. These predictions are part of a simple learning process (Poulton, 1952) whose end result is to modify the absolute temporal component of the response signal. With practice the subject usually advances his response in time. The ability of the human operator to think and extrapolate forward in time orients the process of control around future states of the environment. Kelley (1968) outlined a basic characteristic of manual control.

> Manual control systems function to reduce the difference between what an operator wants to happen to a controlled variable and what he thinks is going to happen unless he institutes a change. (p. 41)

Kelley believes that the human operator's model is a structure built up in the past that he employs to predict the future. Prediction therefore must play a key role in the process of manual control and hence be accounted for in the present tracking study. An index that reflects the subjects' ability to cope with predictable aspects of the target course should be an integral part of the measure used to describe a subject's response.

The following series of experiments utilize a lead-lag index derived from a crosscorrelation function. This index has been recommended by Bennet (1957) and Fitts et al. (1959). The crosscorrelation function differs from the more commonly used autocorrelation function in that the two sets of values being correlated are derived from different time series. Fitts and his colleagues give a very illustrative example.

> . . . as a pilot controls an aircraft in pitch and roll how does his error in pitch relate to his error in roll? A direct way of answering this question would be to obtain continuous records of pitch and roll errors and to compute the crosscorrelation function between them. (p. 630)

When relating stimulus to response the crosscorrelation function describes the lead or lag in the controlling system. For example, if a subject was predicting the stimulus with zero lead or lag, then the crosscorrelation between stimulus and response should be maximum and positive at time, $\tau = 0$. If the subject lagged behind the stimulus then the corsscorrelation function would read a maximum at time τ_n, where τ_n is the average time of the subject's lag.

(3) Signal Composition

Since most complex relations (i.e., waveform patterns) can be expressed as a combination of simple harmonic components the response signals that subjects made during Experiment III and V were subjected to analysis by a Fourier transform. This spectral analysis transforms complex waves into simple sine waves and cosine waves. A general mathematical statement would read:

$$f(t) = \frac{A_0}{2} + \sum_{n=1}^{\infty} (A_n \cos n\omega t + B_n \sin n\omega t);$$

where: A_0, A_n, and B_n = amplitude determining constants called *harmonic coefficients*;

n[†] = integers from 1 to ∞ called *harmonic orders*;

$\omega = 2\pi f$ (with frequency in cps)

This general mathematical statement may be written in two equivalent forms.

$$f(t) = \frac{A_0}{2} + \sum_{n=1}^{\infty} C_n \cos(n\omega t - \phi_n)$$

or

$$f(t) = \frac{A_0}{2} + \sum_{n=1}^{\infty} C_n \sin(n\omega t + \phi_n')$$

[†] When n is unity the corresponding sine and cosine terms are said to be fundamental.

where:

$$C_n = \sqrt{A_n + B_n}$$

and phase relation ϕ_n and ϕ_n' are given by

$$\tan \phi_n = \frac{B_n}{A_n} \quad \text{(expressed in radians)}$$

and

$$\tan \phi_n' = \frac{A_n}{B_n} .$$

Phase angles ϕ_n and ϕ_n' provide timewise relationships among harmonic components.

If the equation that gives the Fourier transform were to be examined, it would reveal four independent pieces of information relating to the waveform.

$$f(t) = \frac{A_0}{2} + \sum_{n=1}^{\infty} C_n \sin(n\omega t + \phi_n')$$

w 1 2 3 4

w: The complex waveform.

1: Amplitude relation to the axis.

2: Amplitude of harmonic after normalizing.

3: Frequency of harmonic.

4: Phase relationship of this harmonic with all other harmonics.

In addition to providing a more complete description of the subject's response, frequency analysis allows for the computation of the "remnant" of the response. This being the part of the subject's produced signal that does not correlate with the stimulus signal. Poulton (1974, p. 30) uses the computed remnant to indicate the strategies employed by the subject during tracking. "The remnant tends to be large when the man uses non-linear strategies . . . . The remnant tends to be small when the man successfully predicts the track and preprograms his response." The remnant of the response was expected to decrease as a function of acquisition trials.

To summarize, three general categories were chosen to describe a subject's response while performing a tracking task. These were consistency of performance, temporal adjustment of performance and composition of the response signal. These categories outlined the indicants of a skillfull performance that were used during the following experiments. In Experiments I through III the interrelationships among these indicants were determined by recording the various response measures simultaneously during a performance on a blind tracking task.

Experiment IV was undertaken to compare the measure of response consistency (within-subject variance at specified time intervals) with the root mean squared (RMS) error the subject displayed while pursuit tracking. The measure of RMS error has been recommended as the best single meausre of tracking performance by several authors. Poulton (1974, p. 34) in his chapter on recommended methods of scoring states that the RMS error obtained from a tracking task (a) is related to the standard deviation of the error, (b) reflects the entire distribution of errors, (c) is relatively compatible with parametric statistical tests, and (d) is positively correlated with modulus mean error. Also an extensive study by Bahrick, Fitts, and Briggs (1957) demonstrated the limitations of the measure time-on-target while showing RMS error to be a better overall measure of tracking performance. A comparison of the standard deviation (SD) of the error and the RMS error has been completed by Fitts et al. (1956) and Bahrick and Noble (1966). The difference between the SD of responses used in the present study and the SD of the error is that the SD of responses is the variance of repeated responses taken at a specific point in time while the SD of error is the average variance of one response taken over a period of time. Fitts and his colleagues found the correlation of RMS and SD of the error to be .82. Therefore, it was expected that the consistency measure used in the present series of experiments would be positively associated to the known measure of performance, RMS error.

EXPERIMENT I

Experiment I examined the changes in performance a subject exhibited while tracking a quasi-predictable signal over a learning period of 13 testing sessions. The coherency of the stimulus course was varied during the experiment. In the first eight testing sessions, one-fifth of the stimulus course was repeated each trial while the remaining four-fifths of the course were random. Changes to the serial order of the repeating sequence were made during the ninth and tenth testing sessions. The stimulus course for the last three experimental sessions was more predictable, since no random selections of sequence were included in the course. During these testing sessions the stimulus signal was comprised of a completely repeating series.

Two measures of skill acquisition were used to monitor the subjects anticipated improvement in performance. The within-subject variance score was used to measure the subject's consistency of movement velocity within each block of trials. Whereas the adjustments that were made during learning in the temporal aspects of the response, were indicated by a crosscorrelation function. The data points that were used to derive these two measures of performance were sampled from equivalent time periods during each trial. In this time period, the stimulus course was also equivalent, therefore, it was possible to compare the subject's responses under varying conditions of stimulus coherence.

Method

Subject

The subject (E.F.) was a female physical education teacher, aged 31 years, who wrote with her right hand.

Apparatus and Task

A blind pursuit tracking task was used in the following experiment. A photograph of the apparatus is given in Figure 1.

A PDP 11/10 computer was used to control the experiment. The interaction between apparatus and computer is shown in Figure 2. The computer was programmed to give variable digital to analog (D/A) signals (ranging from 0 → +5 volts) to the X component of a Statham CRT. The electron beam moved horizontally across the CRT at a predetermined speed. The subject's response involved moving a control lever in a horizontal plane. The response was limited to an angular displacement of 56°. The handle of the control lever was mounted on a radial arm 13 inches (31.2 cm) long and stationed directly in front of the CRT. Attached to the radial arm, at its circumference, was a roller assembly that allowed near friction-free movement.

The radial arm pivoted around a 10K. Ohms, one turn potentiometer and was fixed at the centre of the 56° response segment. A 2.5 volt supply (Electro Model NFBR Filtered D.C. Power Supply) was connected to the poetentiometer, and the output from the potentiometer was in turn connected to an analog to digital converter channel of the computer. Therefore, response movement was converted to voltage change and stored as its equivalent digital value.

The computer was used to control an auditory tone, which acted as an event indicator to the subject. The tone was generated by the

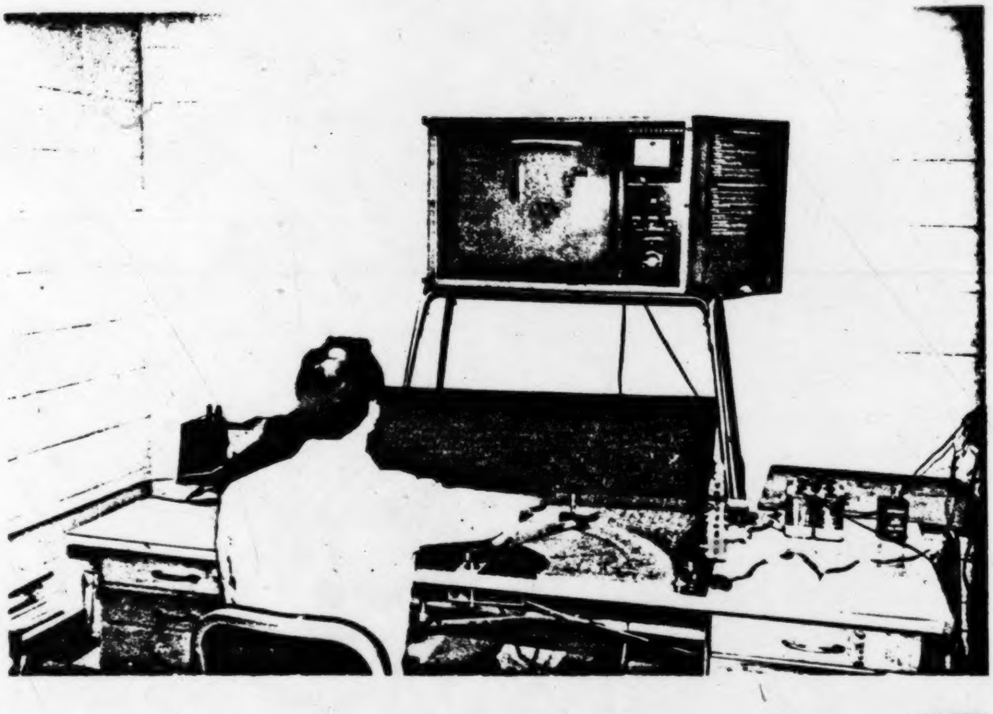


Figure 1. Photographs of the apparatus and task that were used.

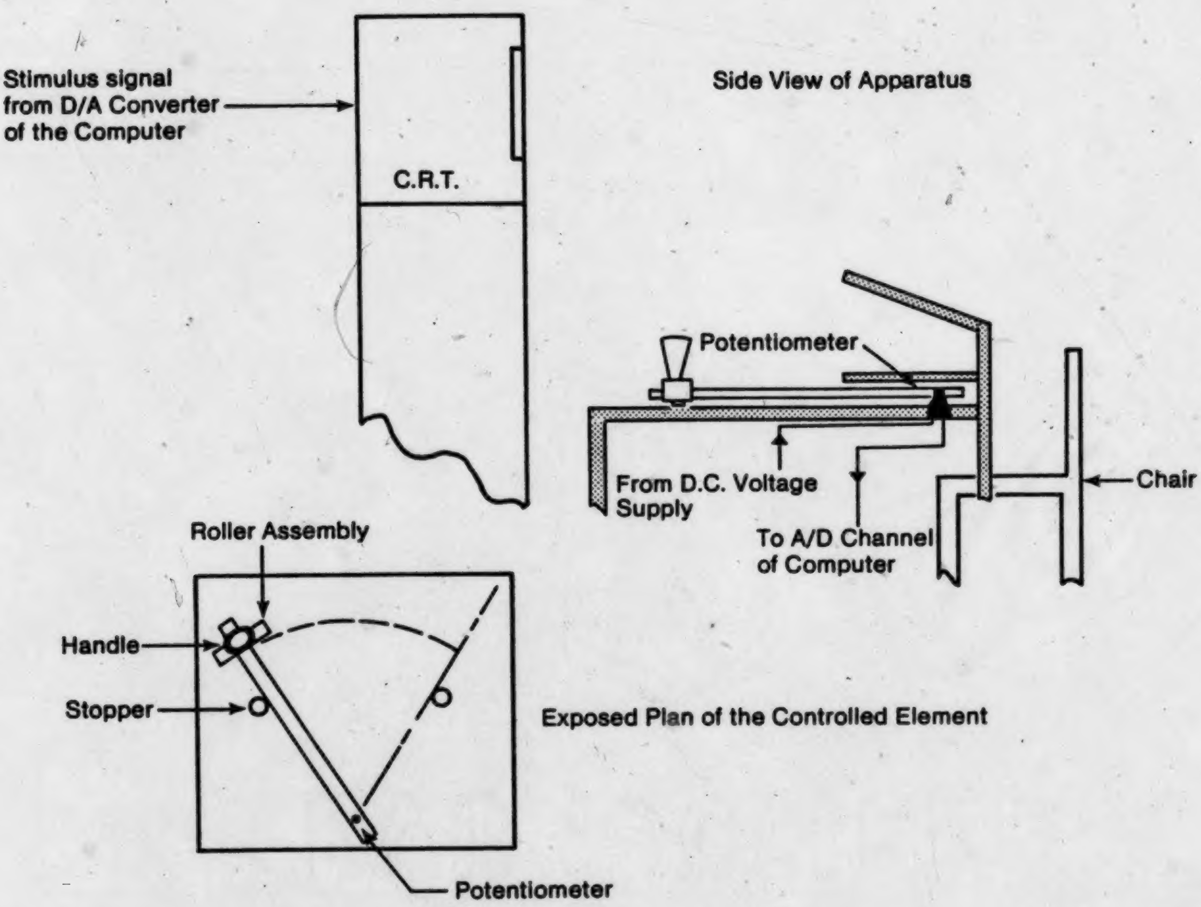

Stimulus signal
from D/A Converter
of the Computer
C.R.T.
Side View of Apparatus
Potentiometer
From D.C. Voltage
Supply
To A/D Channel
of Computer
Chair
Roller Assembly
Handle
Stopper
Exposed Plan of the Controlled Element
Potentiometer

Figure 2. Plan of controlled element and apparatus interface with computer.

computer activating a solid state switch (via a D/A converter). This switch operated an EICO Audio Wave Generator to produce the tone.

The subject was seated in front of the apparatus and placed the palm of her hand over the handle. This allowed only movements about the shoulder joint, the prime movers being the anterior deltoid and pectoralis major muscles. A screen was mounted in front of and above the subject's right arm. This screen permitted only visual information from the stimulus.

The task required the subject to be seated approximately 28 inches (71.1 cm) away from the CRT and hold the control lever in her right hand while tracking the movements of the stimulus. The stimulus was programmed to move to three transition points[†] on the CRT. These positions were fixed equidistantly 6 inches (15.24 cm) apart and centred on the CRT. There were no external markings on the screen to indicate the position of each transition.

The speed of the stimulus beam was 6 inches per second (15.24 cm per second) and time at transition was programmed at 311 milliseconds.[††] One trial consisted of the subject making 50 movements in pursuit of the stimulus beam's path between transitions. The approximate time at task for each trial was between 75 and 80 seconds. Eight trials, separated by a rest interval of 65 seconds comprised one block of trials. Before each block of trials the subject completed a practice trial. During the practice trial the subject tracked 50 movements of the stimulus. The serial order of transition points during this sequence of 50 movements was randomly generated each time by the computer. Therefore, while at one transition point, the likelihood of where the next transition point would be was unpredictable. The experiment spanned a period of 13 days, with the subject completing one block of trials per day.

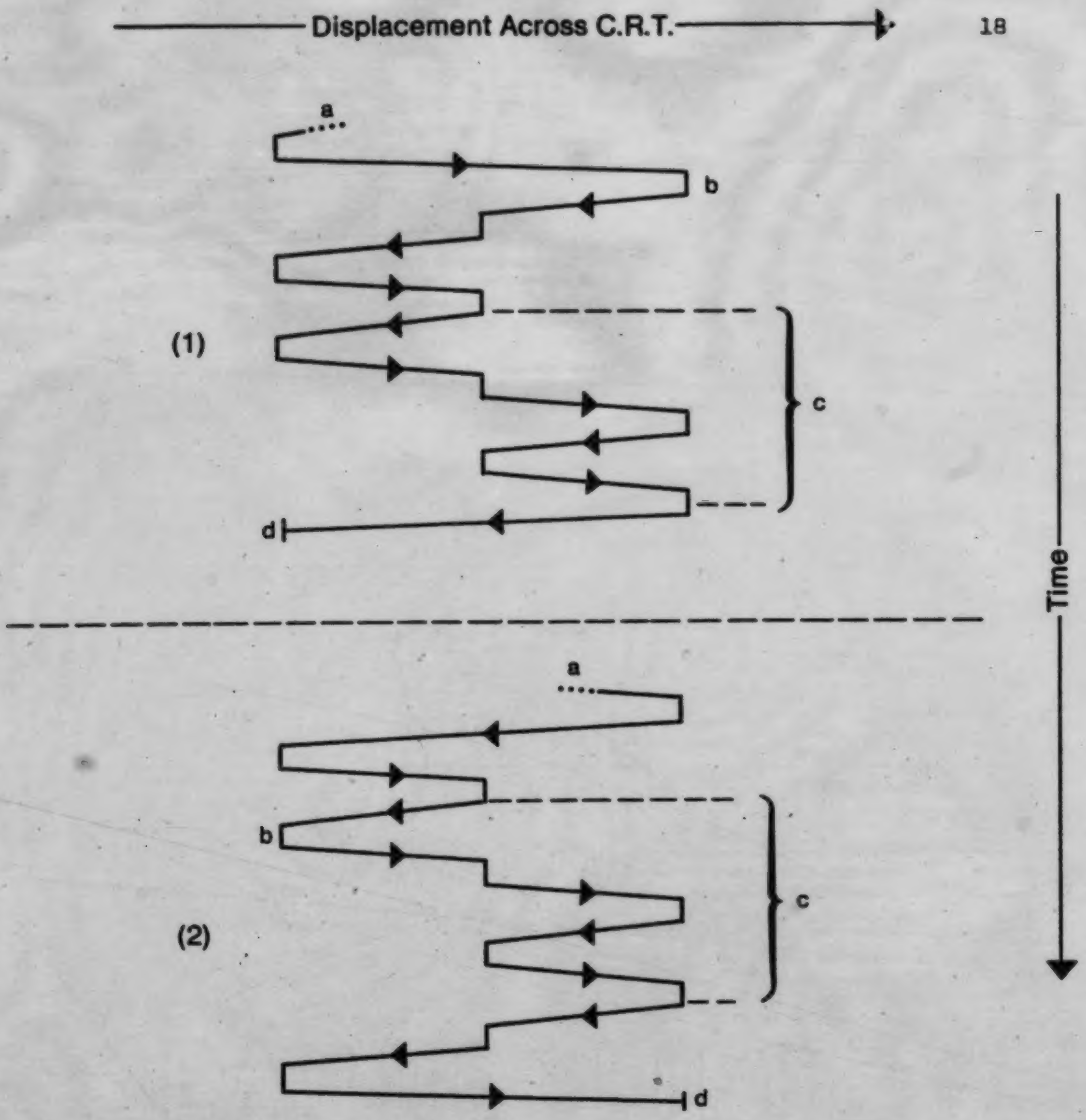
[†] Transition point is defined as the part of the stimulus course that the beam remained stationary for 311 msecs.

[††] The signal can, therefore, be described as a constant velocity ramp track. See also Pew (1974a, p. 22) and Poulton (1974) for description.

The stimulus course of one trial for the first eight blocks was made up of 40 randomly generated movement sequences (different on each trial) plus 10 patterned movements (see Figure 3). These patterned movements were repeated as the last 10 movements of each trial. Responses to these 10 patterned movements were sampled and recorded at a rate of 100 samples per second. The only change during Blocks 9 and 10 was that the serial order of the patterned movements was rearranged (see Figure 3). The 50 movements for trials in Blocks 11, 12, and 13 were made up of the original 10 patterned movements (as in Blocks 1 → 8) repeated five times. Except for the information gained while tracking, the subject was at no time during the experiment given any information as to the predictability of the stimulus course. After each block of trials the subject was encouraged to report as much information about the stimulus course, and the response strategy utilized, as possible. These introspective reports were recorded.

Procedure

An audible tone indicated to the subject that the experiment was to begin. The subject then had two seconds to align the control lever to the appearance of the stimulus beam on the CRT. A second tone preceded the movement of the stimulus by one second. The subject then responded to the stimulus course of 50 discrete movements. A double


Displacement Across C.R.T.
a
b
(1)
c
d
Time
a
(2)
b
c
d

a. End of 40 randomly ordered movements; beginning of the patterned movements.
b. Transition time 0.311 seconds.
c. Movements for which responses were analysed.
d. End of trial.

Figure 3. Stimulus course for the ten patterned movements for blocks 1 - 8, original pattern (1) and for blocks 9 and 10, alternate pattern (2).

tone coincided with the end of the last movement. After a period of 65 seconds rest the subject would again receive a warning tone that the next trial was to begin. At the end of the eighth trial four tones signalled the completion of the block of trials. The subject was then interviewed as to the nature of the stimulus course and the response strategy she used.

Data Analysis

Within-Subject Variance

The variability of the subject's movement velocity was calculated within each block of eight trials for data samples taken over the last 10 movements of each trial. In each trial, 1,420 data points represented angular velocities of movement taken every 10 milliseconds. Therefore at time t_n a block of eight trials would yield eight angular velocities. The variance of these eight values was calculated and then the average of the 1,420 variances was computed for each block of trials.

Crosscorrelation

Comparisons, between movement velocities of Trial 7 Block 13 with Trial 7 in all other blocks, were made via a crosscorrelation function. A real time ($\tau=0$) correlation coefficient between movement velocities of Trial 7 Block 13 and velocities of, for example, Trial 7 Block 1 was labelled T_0. It followed that T_1 was the correlation coefficient between the velocity data points of Trial 7 Block 13 at t_n and Trial 7 Block 1 at t_n+.1 seconds. The correlation coefficient between data points at t_n (Block 13) and t_n+.2 seconds (Block 1) was therefore termed T_2. Time lag relationships between responses during different blocks of trials were examined via this analysis.

Graphical Analysis

To describe the subject's response variations more definitively, actual records of angular velocities were graphed. Trial 7 of each block was used for this analysis, and 3 movements from the last 10 movements of Trial 7 were examined. This part of the course was equivalent in content and serial order for all blocks. The movements analyzed from Blocks 1 → 8 and 11 → 13 are the 5th, 6th, and 7th movements while for Blocks 9 and 10 movements 3, 4, and 5 were used (see Figure 3,c).

Results and Discussion

The subject's movement velocity during the specified patterned movements became more consistent within each block of trials as the experiment proceeded (see Figure 4). A plateau of performance as measured by within-subject variability occurred at approximately Trial Block 6, and the introduction of alternate and repeating patterns seemed to cause the variability to fluctuate about this plateau. According to introspective reports after each block of trials, the subject was not aware of any specific pattern of movements repeating itself during the trials. However, suggestions as to certain course regularities occurred after Trial Block 9. The subject noted that the end location of the stimulus beam had been changed. Upon further questioning the subject was aware of the last movement made toward the end location.

Crosscorrelation functions were calculated to compare Trial 7 Block 13 with all other blocks. From these results it appears that the subject's time lag early in practice decreased over trials (see Figure 5). It is important to note that this decrease in lag is not the result of any intentional strategy as the introspective records show. The results from Block 9 suggest that the subject increased his time lag. This could be due to the change in the serial order of the patterned stimulus movements during the alternating pattern condition.

Other features of response change while tracking are shown in detailed analysis of the velocity curves (see Figure 6). Several of these features are outlined below.

(1) Velocity curves of Trial Block 8 were more similar to the velocity curves of Block 13 than to that of Block 9. The corrections made during Block 8 and 13 at maximum velocity may be a result of the

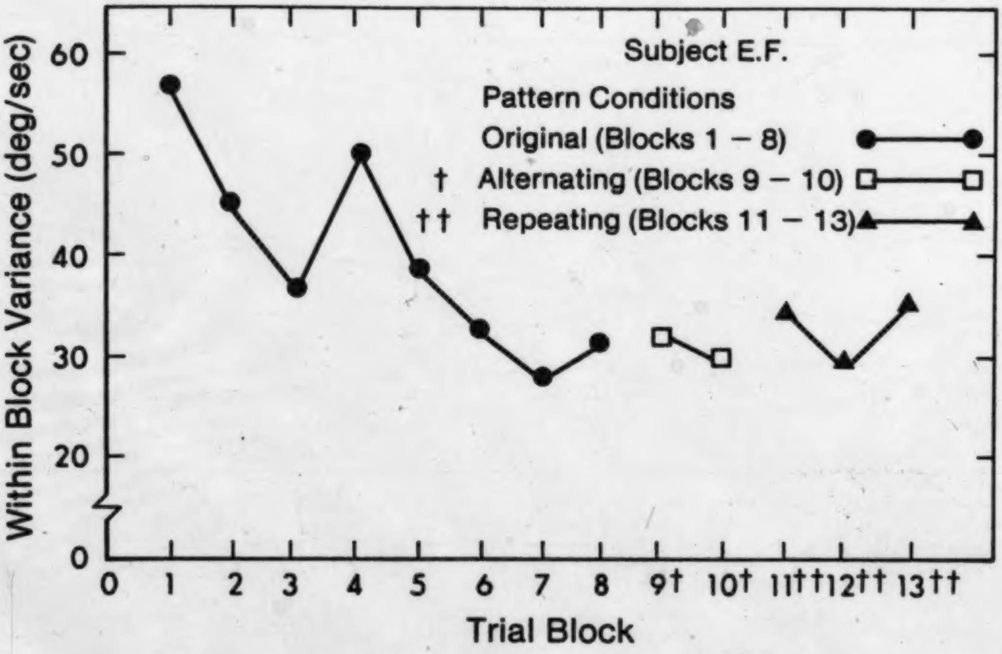


Figure 4. Average within block variance of velocity curves for last ten movements of each trial.

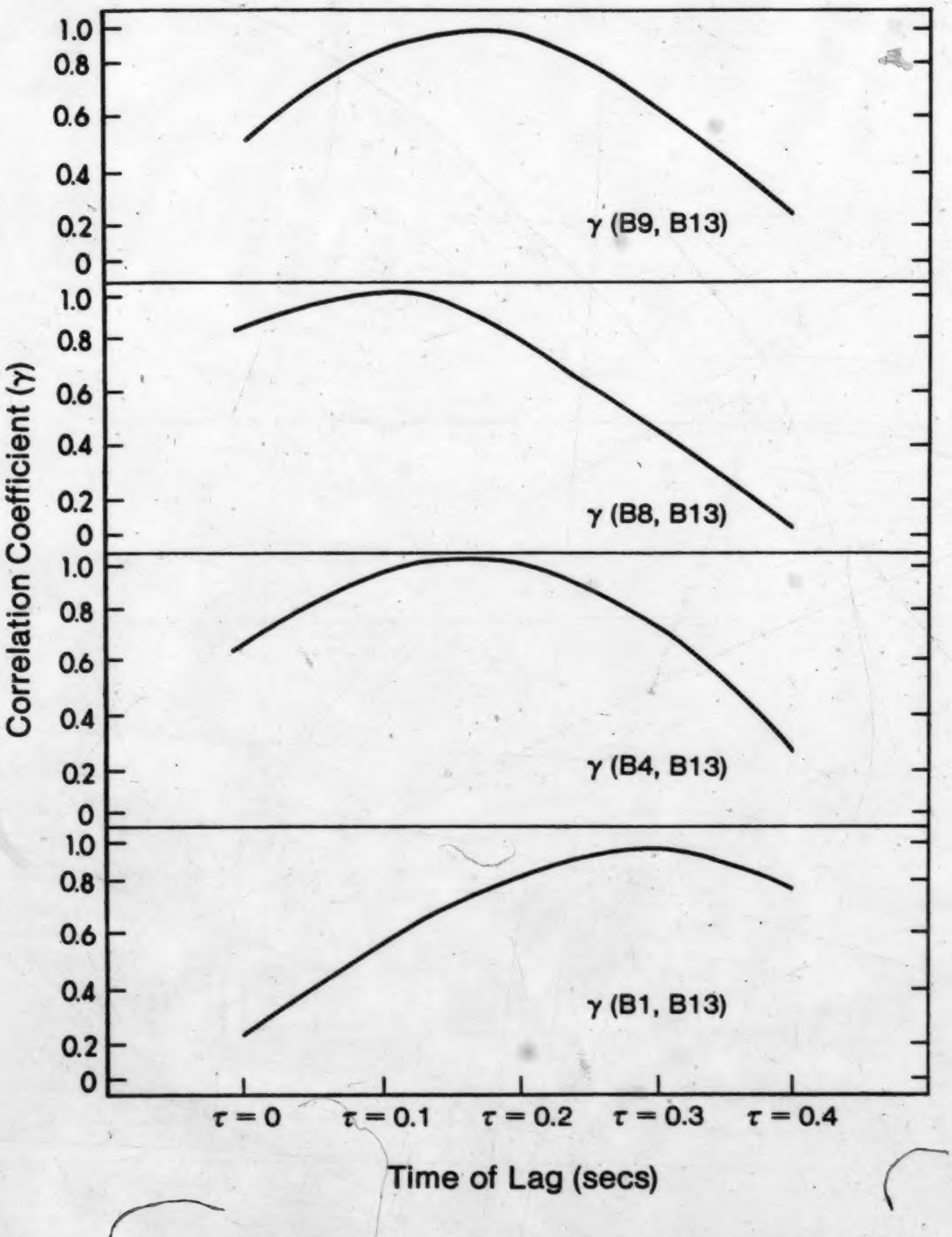


Figure 5. Cross-correlation functions of velocities. The analysed movements in Trial 7 of Blocks 1, 4, 8, and 9 correlated with velocities of Trial 7, Block 13. (Time intervals are advanced by .1 secs from $\tau = 0$ to $\tau = .4$ secs).

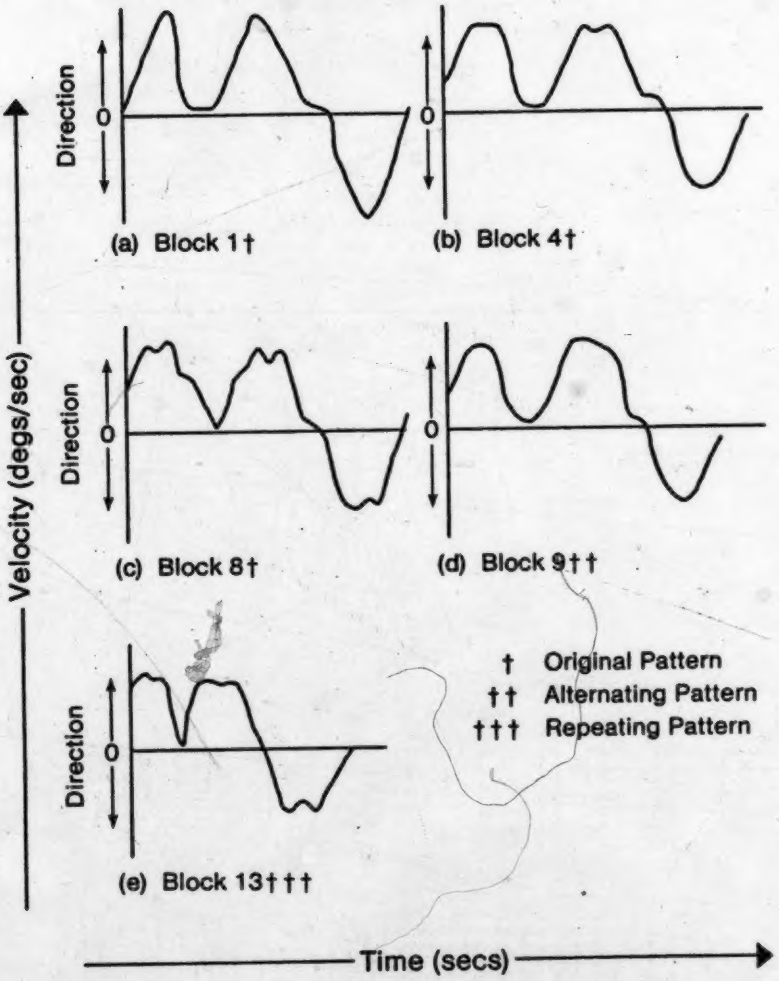


Figure 6. Response records from selected trial blocks. This response was to Stimulus movements 5, 6 and 7 of the original pattern.

subject anticipating the stimulus movements. These corrections were not evident in Trial Block 9.

(2) Early in practice the subject spent more time at transition points (angular velocity = 0). This *time at transition* was reduced later on in practice. Earlier tracking studies by Bartlett (1951) support these findings. He found that ". . . the component movements became altogether smoother and more uniform, and in particular the resting period at the centre was radically reduced" (p. 4).

The time spent at maximum and minimum velocities was analyzed for Trial Blocks 1, 4, 5, 8, 9, 10, and 13 (see Figure 7). It appears from inspecting this graph that the subject decreased the time spent at transition points and also reduced the time spent at maximum velocity as practice proceeded. Variation in this general trend were evident after the introduction of an alternating pattern.

To conclude, it appears that all of the assigned response measures added to the description of skill acquisition. Changes in the subject's response are summarized below.

(1) The subject's movement velocities became less variable over repeated trials.

(2) The subject did not detect any stimulus coherency.

(3) The optimal strategy for completing the task was for the subject to lag behind the stimulus early on in practice. This time lag decreased during extended practice.

(4) Time spent at transition points decreased over trials.

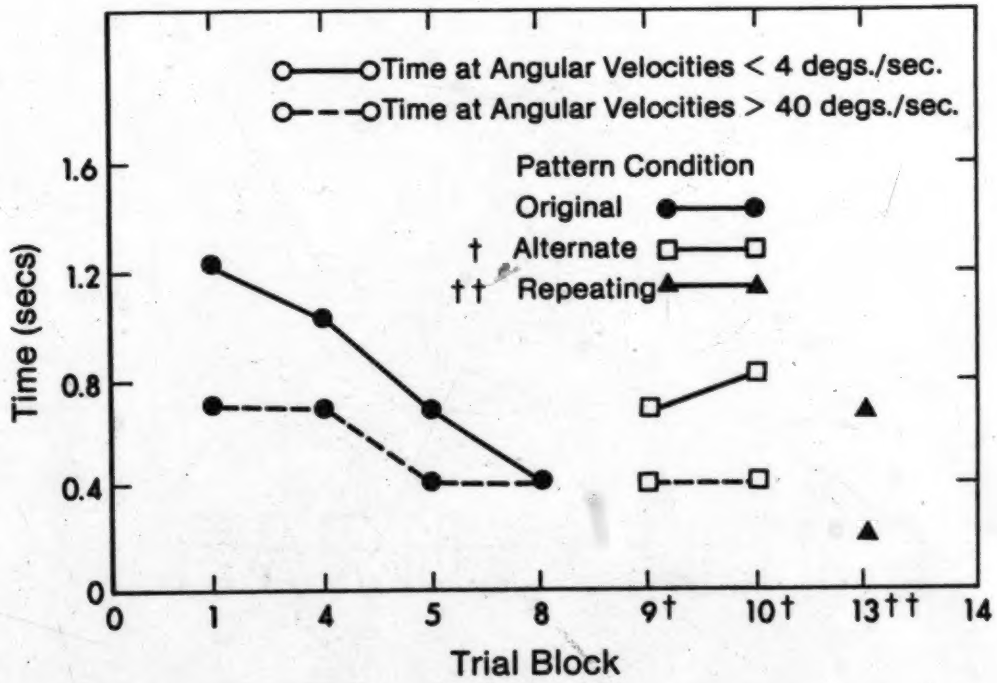


Figure 7. Amount of time spent on angular velocities less than 4 degs./sec. and greater than 40 degs./sec. for analysed movements during Trial 7 of each selected block.

EXPERIMENT II

The patterned movements of the stimulus, that were repeated at the end of each movement list in every trial of Experiment I were not fully detected by the subject. Verbal reports from the subject confirmed this observation. Therefore, in the present experiment, certain stimulus parameters were changed, specifically with a view to help the subjects detect and utilize stimulus course coherency.

The subjects in Experiment II were presented with a patterned list of ten stimulus signals that were repeated five times to make up the stimulus course of one trial.[†] The composition of this repeating pattern included long movements of the stimulus marker at the beginning and end of the repeating pattern. This was done in order to highlight the boundaries of the repeating pattern. It was expected that the experimentally imposed organizational units would therefore become evident to the subjects after several trials.

Ongoing performance measures were once again used as indicants of skill acquisition. The within-subject variability of movement velocity was used as a measure of response consistency. Correlational analyses measured the time relationship between responses made early in practice with responses made later in practice. The subjects' responses were also graphed to examine the displacement and velocity curves obtained during the first few movements of the stimulus pattern. Finally, after each testing session the subjects were given a pencil and paper. They were asked to draw as much of the stimulus course as they could remember and write down any other regularities (i.e., repetitions of the pattern) that were evident from the stimulus course.

[†] c.f. Repeating pattern of Block 11, 12, and 13 of Experiment I (see Figure 3(1)).

Method

Subjects

Three subjects who had not taken part in the previous study, volunteered to participate in this experiment. The subjects were two males (G.C. and F.H.) and one female (M.H.). All were undergraduate physical education students who wrote with their right hand and ranged in age from 18 years to 20 years.

Apparatus and Task

The only change made to the apparatus used in Experiment I was that the response segment of the control lever was increased in range from 56^0 to 112^0. The speed of the stimulus beam's movement was increased to 9 inches per second (22.86 cm per sec), with the time at transition being decreased to 120 milliseconds.

One trial consisted of the subjects making 50 movements in pursuit of the stimulus. One movement was again defined as tracking the stimulus marker's path between transition points. The total time at task for each trial was 46 seconds. Eight trials each separated by a rest interval of 30 seconds comprised one block of trials.

The subjects completed a practice trial before each block of trials. During this practice trial the subject tracked the stimulus marker's movements of 20 reversals between the right and left transition points. Hence the serial order of stimulus events was very predictable. Responses to this predictable stimulus were sampled and recorded (sampling rate of 100 data points per second). Between the end of the practice trial and the start of the first trial proper, the subject rested for 20 seconds. The experiment spanned a period of seven days, with the subjects completing one block of trials per day.

The stimulus course for each testing trial was similar to that of Blocks 11, 12, and 13 of Experiment I. The 50 stimulus signals comprising one trial were made up of the 10 patterned signals (see Figure 3(1)) repeated five times. Responses to the middle 10 stimulus signals (21 to 30) were sampled and recorded at a rate of 100 samples per second.

After the first block, and before and after the remaining blocks of trials, the subjects were given a pencil and paper and asked to draw out the patterned movements made by the stimulus marker. Movements of the stimulus marker were depicted as horizontal lines while time at transition were represented by vertical lines (c.f. Figure 3). The subjects were then asked to add any further comments that were relevant to the nature of the stimulus and their ability to respond to the stimulus.

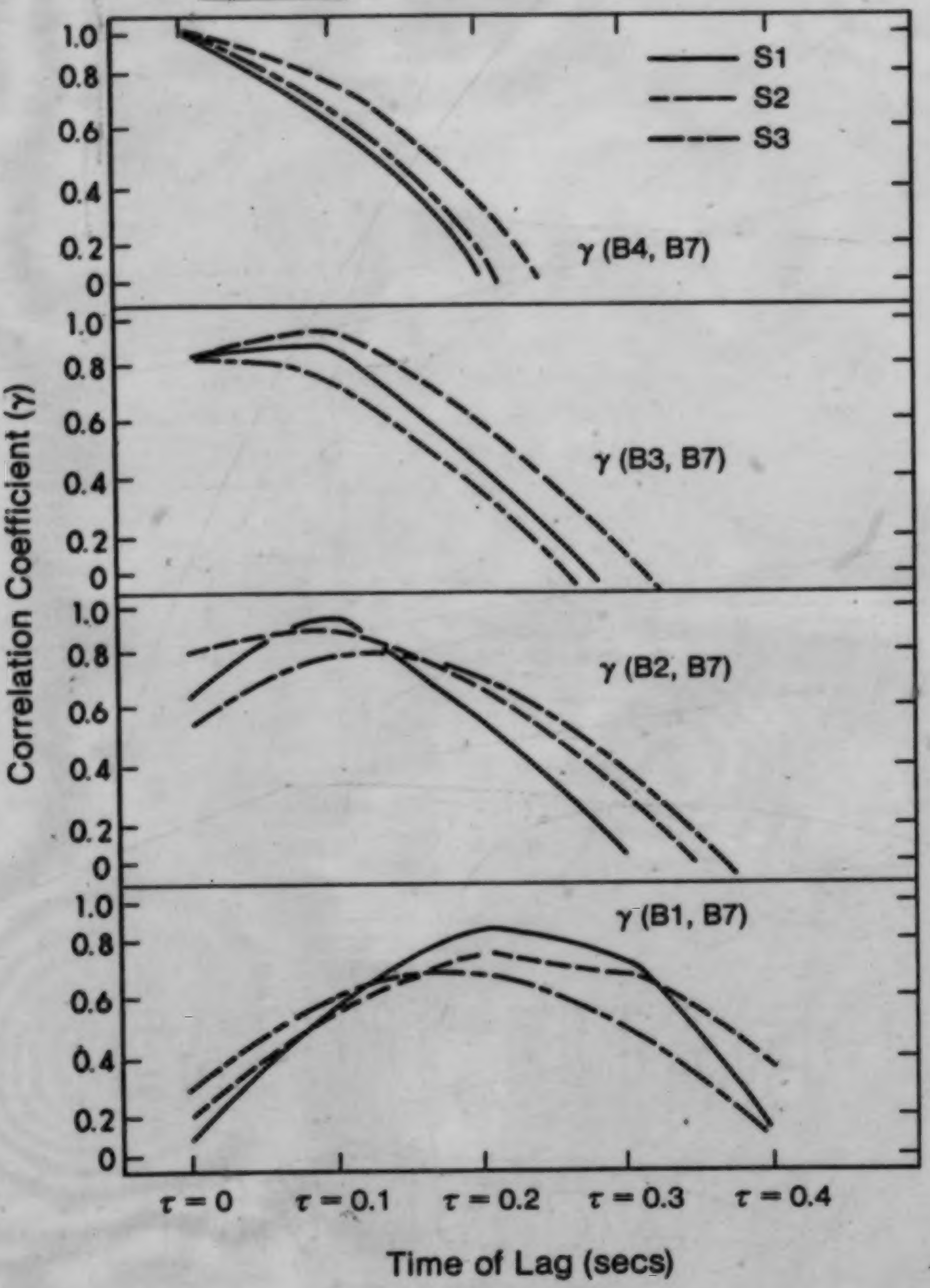


Figure 8. Cross-correlation of responses made during Block 7 with Blocks 1, 2, 3 and 4. (Time intervals are advanced by 0.1 secs from $\tau = 0$ to $\tau = 0.4$ secs).

Results and Discussion

Following the first block of trials and preceding the second block, subject 1 (F.H.) did not detect any repeating sequence and could not reproduce, using pencil and paper, any of the movement list. Subject 2 (M.H.) and subject 3 (G.C.) on the other hand recalled incorrect and incomplete patterns. However, after the second block of trials all three subjects correctly reproduced the sequence of the repeating stimulus signal by drawing its graphic representation. All graphic reproductions that were completed by subjects after the second block of trials were accurate with respect to sequence, but all three subjects sketched in excess of 15 movements before reporting any repetition of stimulus course information. It was not until the end of Block 3 that the subjects recalled 10 movements as an organized unit. The long movements (movements 1 and 10) were used by all subjects to delineate the beginning and end of each organizational unit. The conclusions that can be drawn from these pencil and paper records are that all subjects were able (after a short learning period) to detect the coherency in the stimulus course, although the exact number of times the stimulus pattern of 10 signals repeated itself was never correctly reported throughout the experiment.

An indication of how subjects utilized this stimulus course coherence can be gained from examination of the crosscorrelation functions of responses using Block 7 as the criterion scores (see Figure 8). All three subjects reduced their time lag during the first three blocks of trials. The apparent improvement in the memorial representation of the movement sequence appears to have aided subjects in using predictions concerning the sequence of movements. Crosscorrelation functions between the highly predictable signal of the practice trial and the responses made to these signals were computed. When response velocities made during the practice trial preceding Block 1 and the practice trial's stimulus course were compared, the crosscorrelation funcuntion was maximum and positive when τ=175 milliseconds (i.e., a transmission lag of 175 milliseconds). However, when the responses to the practice trials prior to Block 3 were used to make comparisons with the predictable stimulus, the crosscorrelation was maximum and positive when τ=0 (i.e., stimulus and response were coincident). Therefore, the phase relationship between responses made during the testing session, and the phase relationship between stimulus and response made during the practice trials show similarities in trend. That is, when the correlation coefficient was maximum and positive for a specific value of τ, that value of τ was equivalent in both analyses. However the actual function itself was not equivalent. As expected the crosscorrelation function obtained when comparing responses was higher ($\gamma \geq 0.70$) than a function that was obtained from the comparison of stimulus and response ($\gamma \geq 0.60$). This appears to be due to the nature of the stimulus signal that was used. The constant velocity ramp track does not approximate human tracking behaviour. The subjects attempted to impose a waveform pattern upon the response, thus smoothing out their performance while meeting the demands of the task. Therefore as practice proceeded the response was shaped toward a subjective criterion of smooth performance.

The intertrial correlation matrices for the three subjects are shown in Table 1. Without exception, every matrix has a superdiagonal

Table 1

Intertrial Correlations of Movement Velocities for the Analysed Movements in Trial 7 of each Block of Trials

Block	1	2	3	4	5	6	7
Subject 1 (F.H.)							
1	----	.65	.49	.38	.21	.12	.09
2		----	.88	.83	.65	.54	.58
3			----	.89	.86	.78	.81
4				----	.84	.78	.77
5					----	.94	.93
6						----	.92
7							----
Subject 2 (M.H.)							
1	----	.53	.48	.19	.21	.23	.18
2		----	.93	.80	.82	.80	.78
3			----	.89	.84	.85	.84
4				----	.94	.95	.95
5					----	.97	.96
6						----	.97
7							----
Subject 3 (G.C.)							
1	----	.71	.54	.29	.08	.22	.29
2		----	.76	.48	.32	.47	.53
3			----	.86	.74	.79	.81
4				----	.93	.91	.90
5					----	.86	.82
6						----	.92
7							----

Note. Trial 7 of each block was selected for comparisons.

form,[†] with the lowest correlations located in the top right hand corner of each matrix. The correlations decrease along the rows to the right and up the columns to the top of the matrix. Responses that were made to trials late in practice (Blocks 5, 6, and 7) were more positively related to each other than were responses made to trials early on in practice (Blocks 1, 2, and 3). These results substantiate Gentile's (1972) proposition that during closed skill acquisition, movement patterns are tightly distributed within a narrow bandwidth of performance.

The three subjects used a different range of angular displacements, although the instructions given were quite specific (i.e., "keep the movement of the control lever coincident with that of the stimulus marker"). The average maximum angular displacements used in both practice and testing trials are shown in Figure 9. The range of displacement used by F.H. is considerably less than that used by M.H. and G.C.. The perceived distance moved by the stimulus marker must not have been considered an important cue for the subjects to use. One possible explanation for the variation in angular displacement is that the subjects moved the response arm for a specified time period, as opposed to a specified distance. This time period being dependent upon the frequency of the stimulus signal and the ability of the subjects to track accurately at this frequency.

The average angular displacements used during the testing trials (long and short movements) are similar to the displacements used by subjects on practice trials (only long movements). This would indicate that the inclusion of the short movements during the testing trials did

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[†] For a brief review see Appendix C.

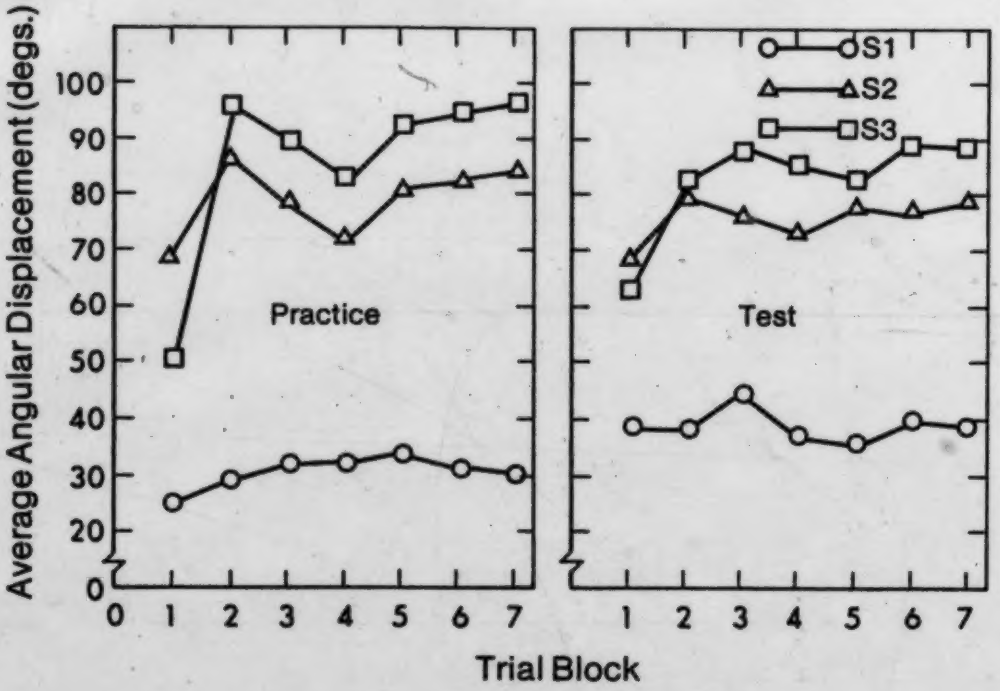

Figure 9. Average angular displacement for practice trials and test trials.

not "compact" the overall movement displacement used by subjects. Furthermore, none of the subjects reduced their originally selected response arc during the experiment. Hence the angular velocity of the tracking response was not reduced during the experiment. The reduction in within-subject response variability cannot therefore be attributed to a reduction in the subject's movement velocity. In fact, all three subjects increased their angular displacement following Block 1 and displayed a corresponding increase in response consistency following this block of trials.

The within-subject variance of response velocities decreased over the seven blocks of trials (see Figure 10). All three subjects show evidence of this trend, although the rate of decrease was dependent upon the initial angular displacement (hence angular velocity) that the subject selects. The dramatic decrease in variance of M.H. and G.C. emphasize the independence of this measure of movement consistency for individual subjects. With practice, subjects responding at a relatively fast rate can achieve a consistency of movement equivalent to that of a subject who responds to the same stimulus more slowly.

The response velocity and displacement graphs were compiled for Trials 7 of each block of trials. These response profiles for the first four movements of the patterned sequence are shown in Figures 11 through 13. Comparisons were made, for each subject, between responses produced during Trial 7 Block 1 and responses made in the corresponding real time frame during Trial 7 Block 7. All three subjects increased time spent at maximum velocity, while attempting to decrease the time spent at transitions between movements. During Block 1, M.H. and G.C. used corrective movements midway through the first movement (long move-

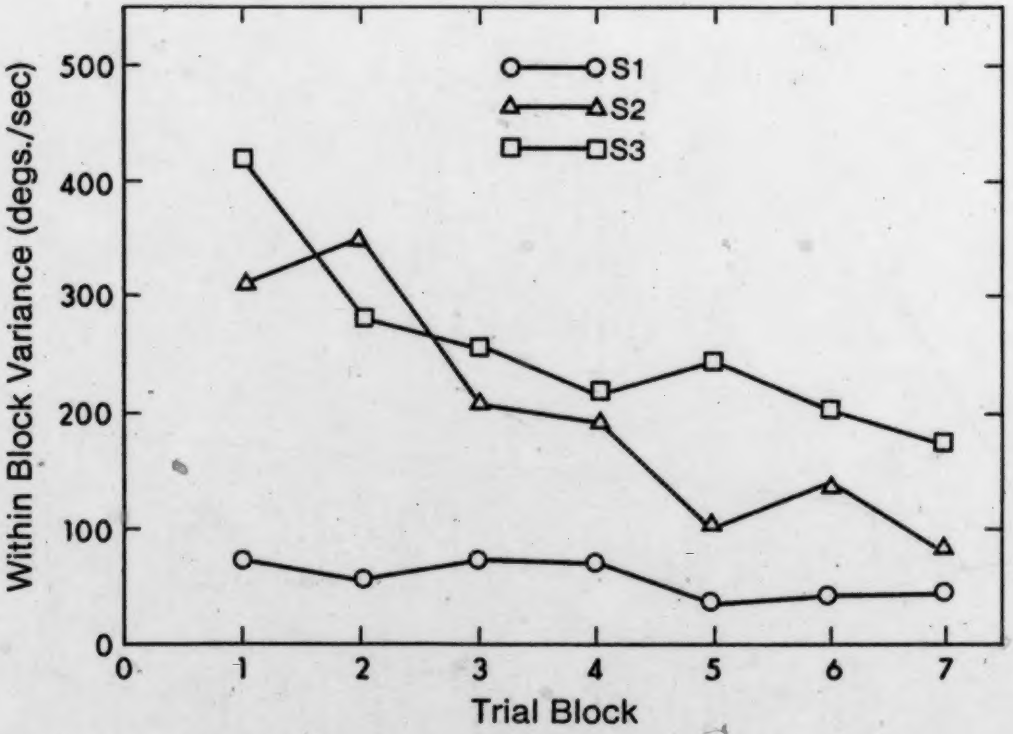

Figure 10. Average within block variance for response velocities, for S1, S2 and S3.

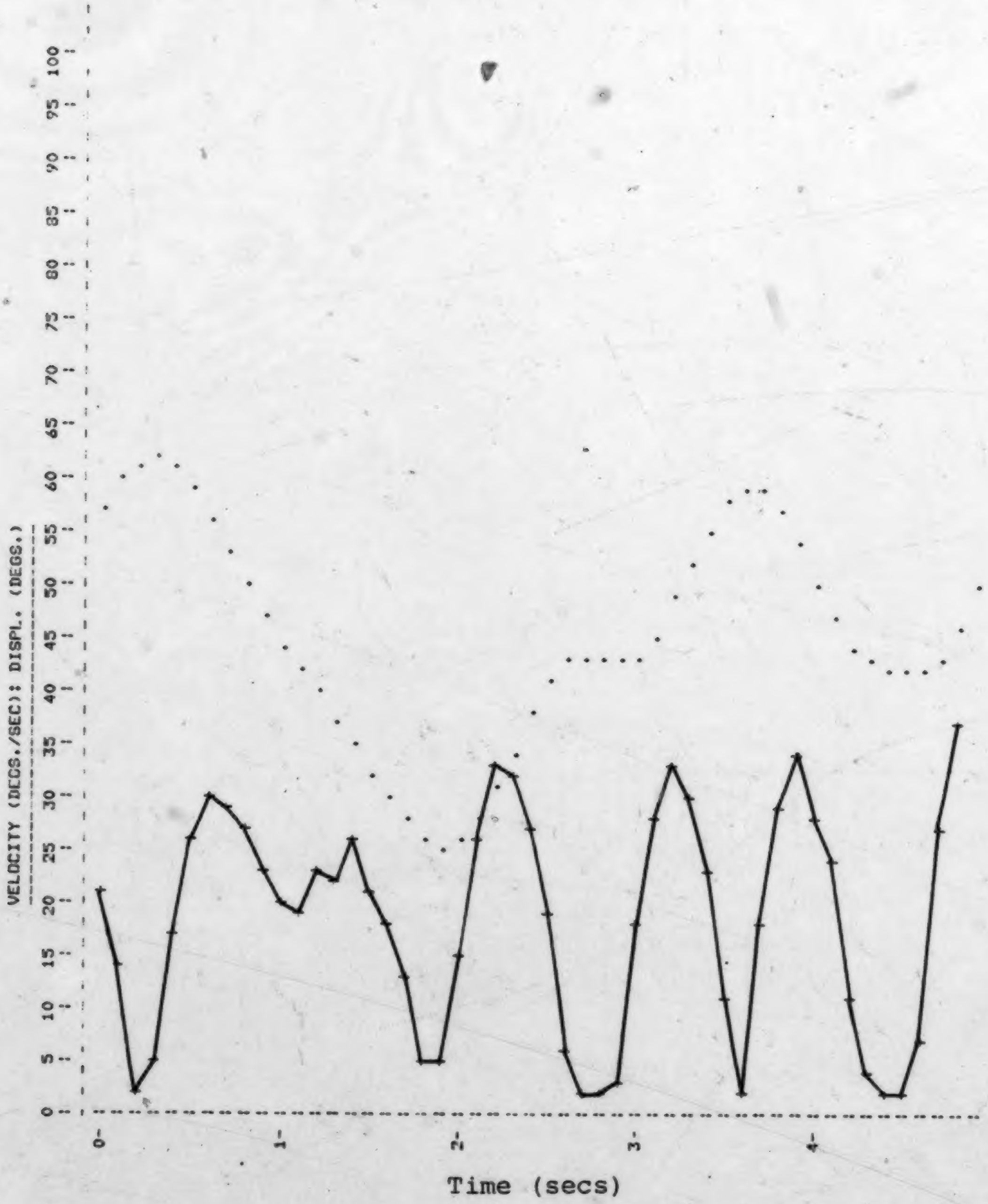

Figure 11a. Displacement and velocity curves for Subject 1 during movements 1 to 4 in Block 1.

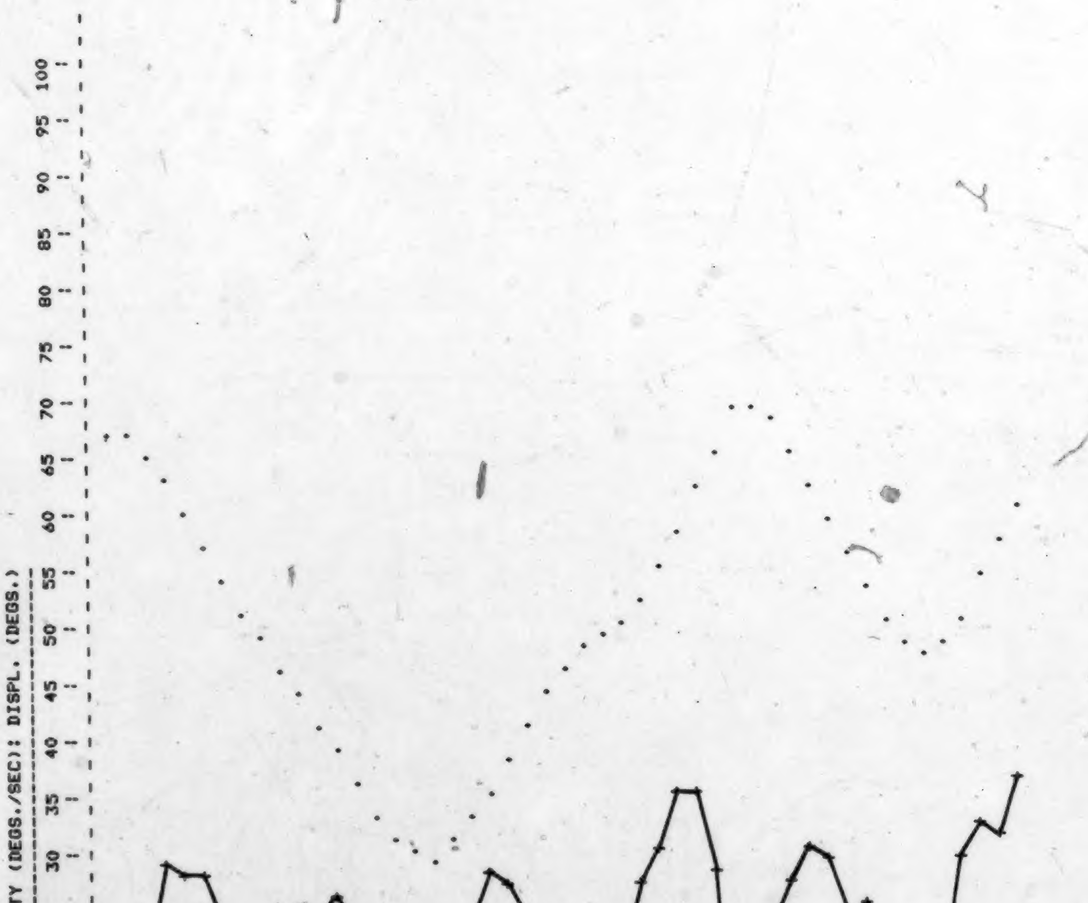

Figure 11b. Displacement and velocity curves for Subject 1 during movements 1 to 4 in Block 7.

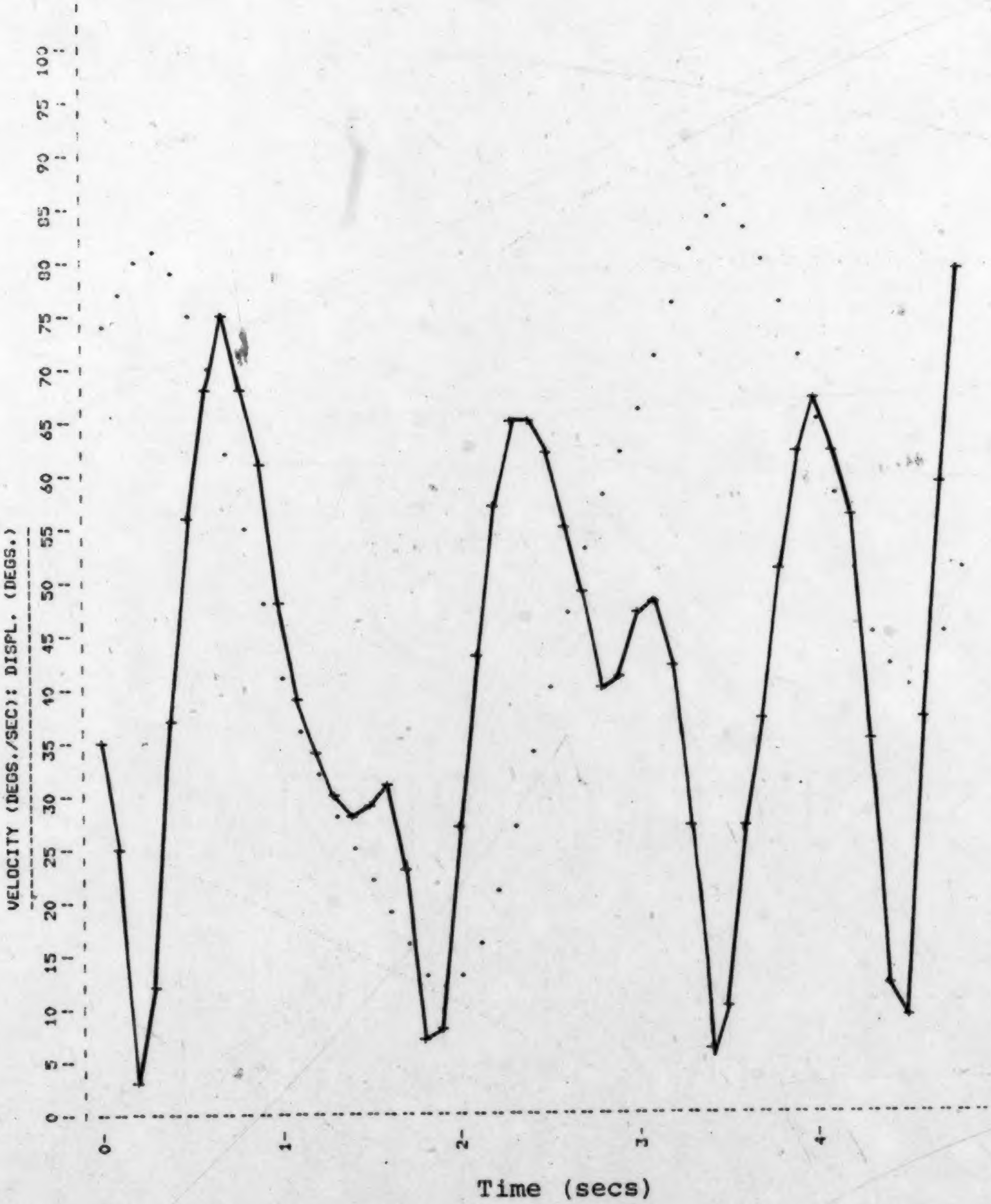

Figure 12 a. Displacement and velocity curves for Subject 2 during movements 1 to 4 in Block 1.

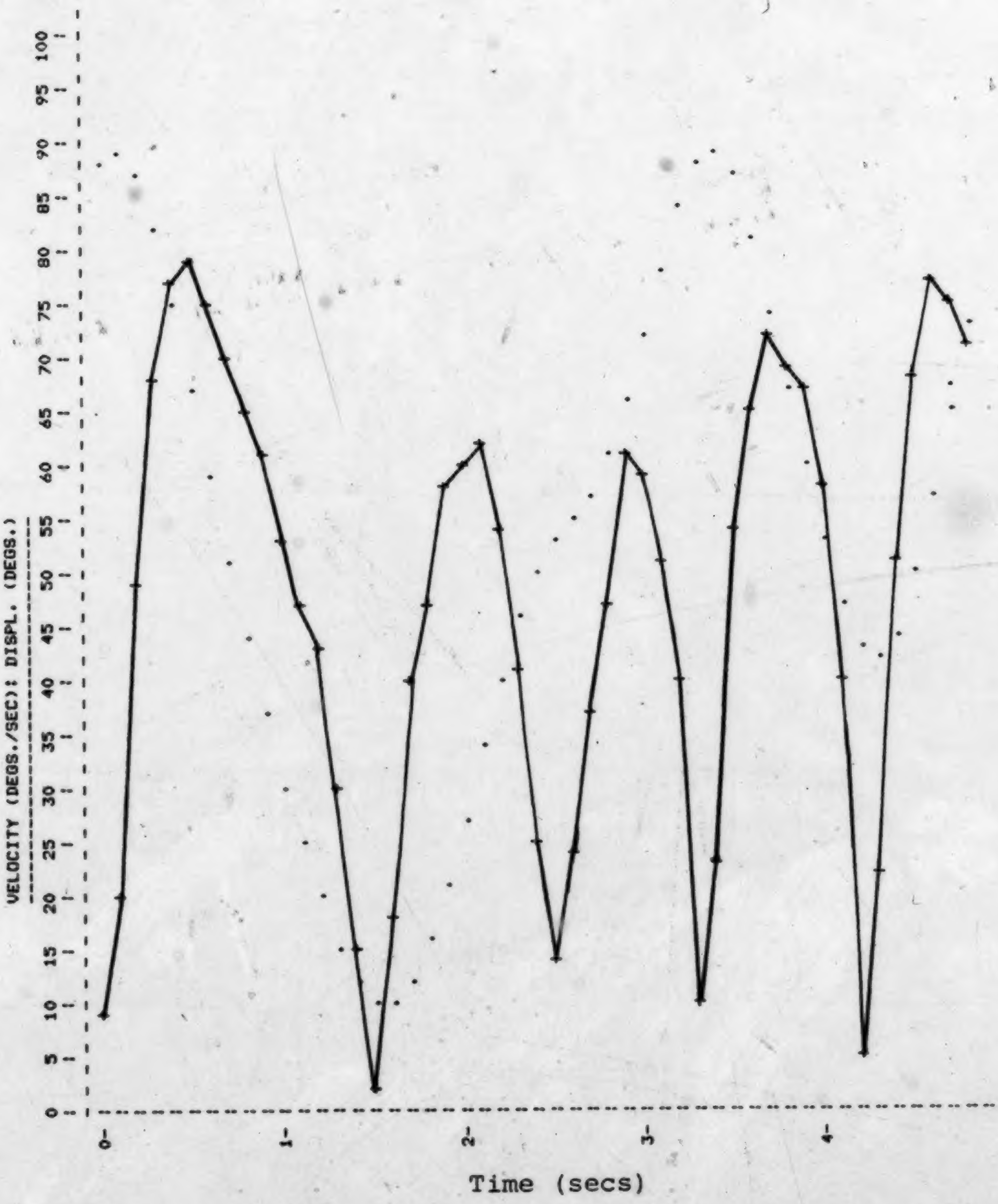

Figure 12b. Displacement and velocity curves for Subject 2 during movements 1 to 4 in Block 7.

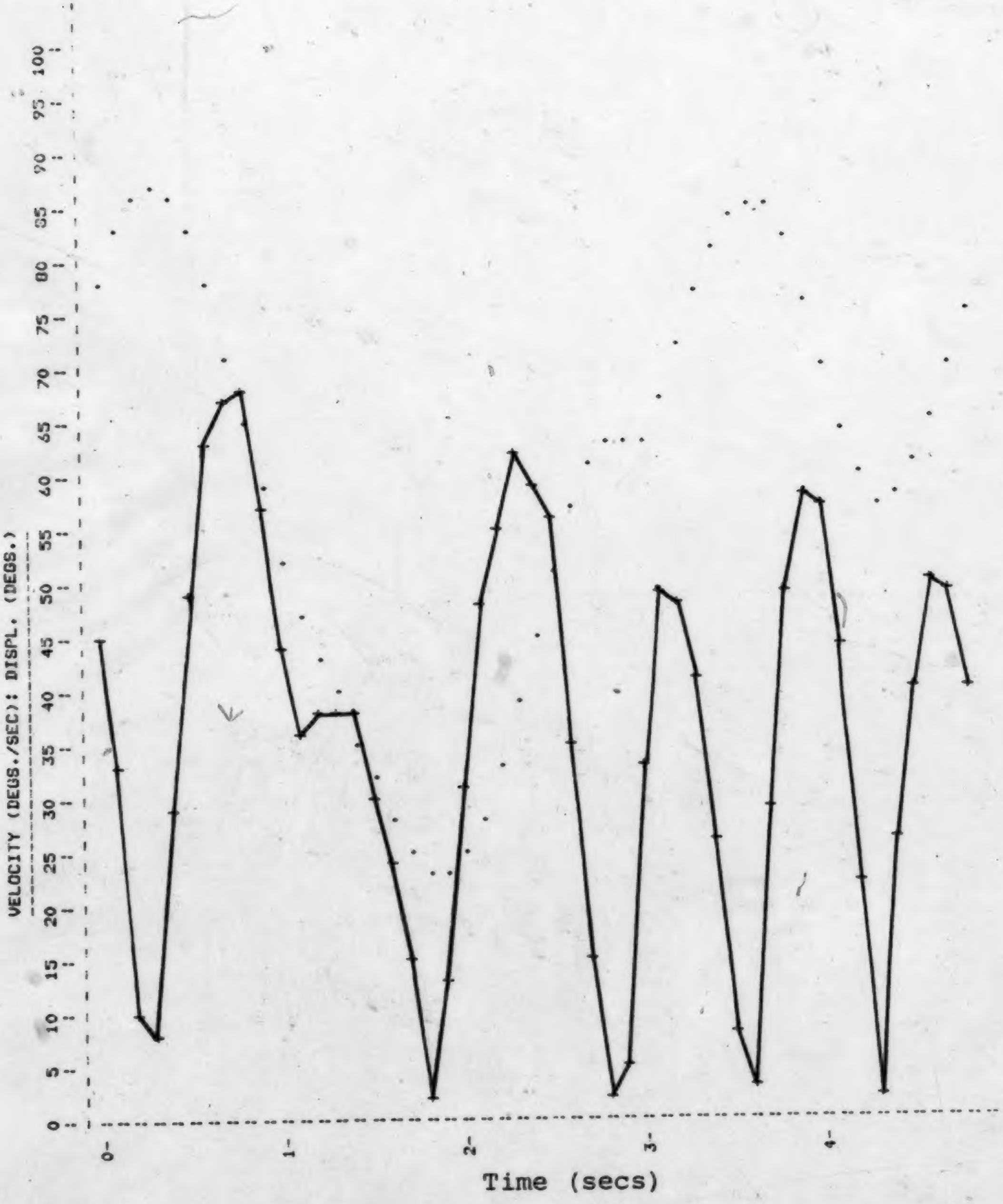

Figure 13a. Displacement and velocity curves for Subject 3 during movements 1 to 4 in Block 1.

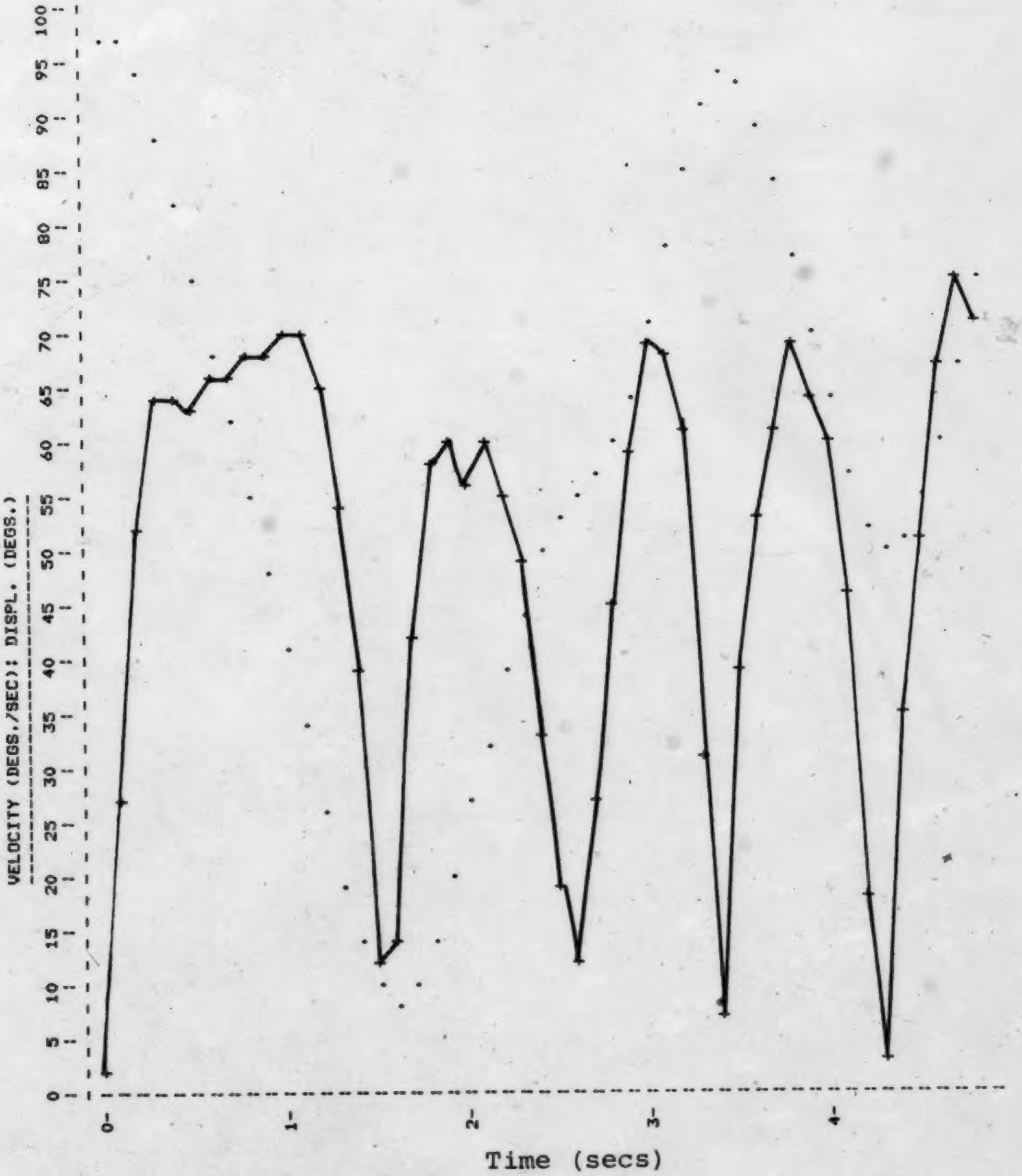

Figure 13 b. Displacements and velocity curves for Subject 3 during movements 1 to 4 in Block 7.

ment) of the pattern. This could be attributed to event uncertainty (i.e., was the stimulus marker going to stop at the middle transition point?). However, no corrective movements were evident while these same subjects responded to the same stimulus course during Block 7.

In summarizing, the following statements can be made:

(1) With practice on the tracking task used in this experiment, the subjects developed an increasingly consistent movement pattern.

(2) Reportable knowledge of the composition of the stimulus pattern aided the subjects in achieving movement consistency.

(3) The optimal strategy for subjects to adopt early in practice was one of "following behaviour". The corresponding time lag decreased over trials.

(4) In their attempts to become more efficient performers, the subjects smoothed out their response pattern by reducing the time that was spent at transition points.

EXPERIMENT III

An increase in movement consistency was achieved by subjects, after practice on the blind pursuit tracking task used in the first two experiments. Consistency was defined with respect to a measure of ongoing performance termed within-subject variability. Whereas the previous experiments in this series have been concerned with overall variability of the movement sequence, Experiment III was undertaken to investigate several questions that remained unanswered with respect to the locus of response variance within a movement sequence. The major focus of the present study was to examine the profiles of response variability that the subject displayed during a block of trials. Two specific questions were of concern: (a) where are the major sources of variation located in a movement[†] that is part of a movement sequence; and (b) what effect does practice have upon the profile of response variation within the movement?

The stimulus signal used in the previous two experiments was a constant velocity ramp track. While pursuing this track early in practice, subjects exhibited discontinuous tracking behaviour. This "novice-like" behaviour was exemplified by such response characteristics as extended periods of time spent at transition points, long periods of acceleration and deceleration, and extensive corrective movements. Later in practice the subjects reduced the time spent at transitions. The smooth performance that was developed by experienced subjects, however, (i.e., blending one movement into the next) did not approximate the stimulus signal. The responses of experienced subjects approached that of a composite sinusoidal wave as opposed to a constant velocity course. Although these developments in response characteristics were to be expected, the tracking behaviour that exemplified the novice performer could have been solely due to the nature of the stimulus. For this reason, a composite sinusoidal waveform[†] was used as the stimulus signal in Experiment III.

[†] Defined as the response to a stimulus marker's movement between reversals.

The problem of subjects choosing their own angular range of movement has been discussed in Experiment II. In the present experiment an "amplitude training" task was given to the subject before each block of trials. As the subject tracked a sine wave stimulus[††] an audible tone was used to indicate reversal positions of the response. If the response arm failed to reach the required amplitude, the stimulus marker would remain stationary until the response amplitude matched the required value. Upon reaching the required amplitude the tone would sound and the stimulus marker would continue its course. It was expected that this training would standardize the range of movement that the subject used.

[†] $f(t) = 50 - 35\sin(\omega t-.75) - 20\sin(3\omega t-1.5) + 10\sin(5\omega t-.75) - 7\sin(7\omega t-.75)$.

[††] Equivalent to the fundamental harmonic of the test stimulus $f(x) = 35\sin\omega t$.

Method

Subjects

One male, physical education graduate (A.D.) was used in this study. He had no previous experience in tracking studies. The subject was 23 years old and wrote with his right hand.

Apparatus and Task

The apparatus used in Experiment III has been described earlier (see Experiment II) and can be seen in Figures 1 and 2 (there were however certain task variations). The periodic stimulus function F(x) was given by the equation:

$$f(t) = 50 - 35\sin(\omega t-.75) - 20\sin(3\omega t-1.5)$$
$$+ 10\sin(5\omega t-.75) - 7\sin(7\omega t-.75).$$

A graph of this function can be seen in Figure 14. The harmonic coefficients, that determine the amplitude of each harmonic component, are given in the digital values supplied by the computer's digital to analog converter. The time for one complete period was 6.5 seconds and it was repeated 20 times. The responses made to the stimulus signal's tenth period were sampled at a rate of 100 per second. This sampling commenced at the time of the reversal point that began each period and continued for 7.5 seconds. This procedure allowed a complete period of the response function to be sampled and extracted from a data base of 750 points.

The time at task for one testing trial was 130 seconds. The subject completed a block of trials at 9:00 a.m. and 1:00 p.m. every day for five days. Therefore a total of 10 blocks of trials were used for this experiment.

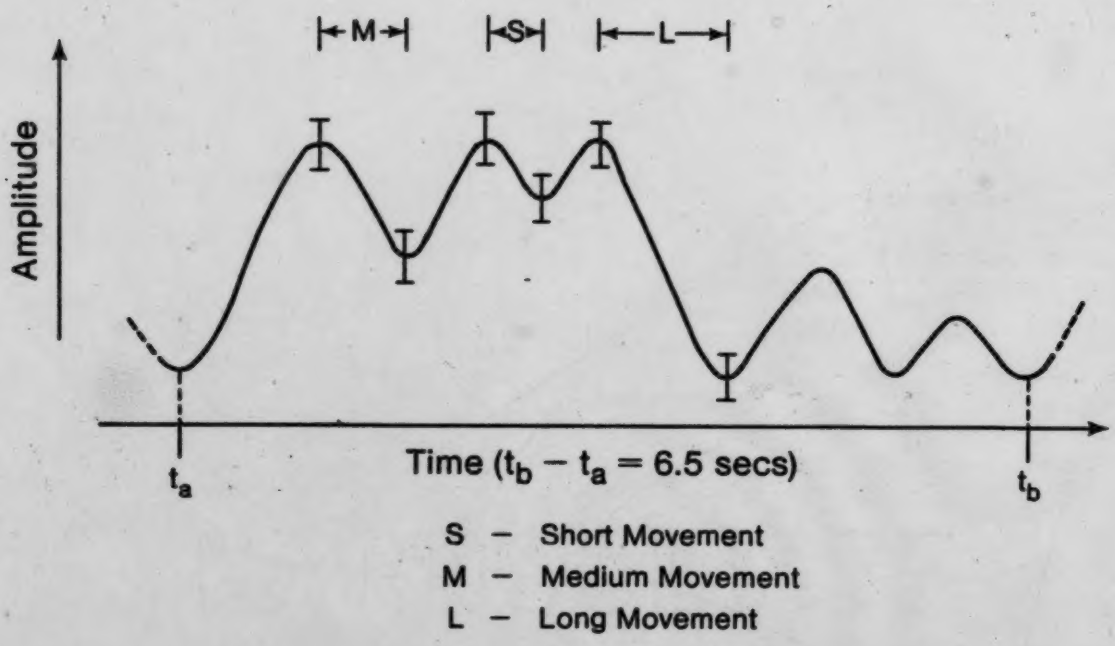

Figure 14. The composite sinusoidal stimulus signal with a period of 6.5 seconds and given by the formula.
$f(t) = 50 - 35(\omega t - 0.75) - 20(3\omega t - 1.5) + 10(5\omega t - 0.75) - 7(7\omega t - 0.75)$.

Before each testing session the subject was given two different practice sessions at tracking a predictable waveform ($f(t) = 35\sin\omega t$). The first was an amplitude training session. While tracking the stimulus, the subject was required to match an experimentally defined reversal position. The computer was programmed to prohibit the stimulus marker's progress from the reversal point unless the subject's response matched the predefined amplitude. When this requirement was fulfilled, a tone was initiated by the computer (via an analog signal from the computer) and the stimulus course proceeded to the next reversal. The subject was instructed to track the stimulus and keep the signal moving as continuously as possible. This was possible because the subject was in partial control of the stimulus marker's movement at the reversals. One amplitude training session consisted of the subject tracking 20 stimulus reversals. A second training session involved tracking the sinusoidal stimulus signal for a period of 80 seconds. The responses to this course were sampled every 10 milliseconds. A time period of 10 seconds separated the amplitude training from the sine wave tracking session. Total time for one complete experimental session (amplitude training, sine wave tracking, and seven testing trials) was approximately 40 minutes. After each block of trials the subject was encouraged to report as much information about the stimulus course as possible.

Procedure

A long audible tone (1.25 secs.) indicated to the subject that the experiment was to begin. The subject then had two seconds to align his response arm to the appearance of the stimulus marker on the CRT. This alignment was accompanied by a short tone (.04 secs.). The subject then responded to the amplitude training session, in which the tones at the reversal points were of short duration (.04 secs.). The commencement of the amplitude training was signalled by a double tone (long duration). The subject then rested for 10 seconds before a long tone indicated the beginning of the sine wave tracking session. The subject received two further long tones at the end of this session and waited for a further 20 seconds before four long tones signalled the beginning of the test trial. Two seconds were allocated for the subject to align his response arm with the marker that was shown on the CRT. A long tone then delineated the beginning and end of seven test trials. The time period of 30 seconds between each test trial allowed the subject to rest and the computer to store the sampled data. At the termination of the entire session four long tones were given. The subject was then interviewed with regard to the nature of the stimulus.

Data Analysis

Fourier Analysis

The Fourier coefficients for the periodic function were calculated by means of harmonic analysis. This analysis utilized the trapezoidal rule for integration (Gaskell, 1958). The Fourier coefficients of the function F(x) were found by evaluating the integrals $\int_{-L}^{L} f(x) \cos\frac{n\pi x}{L}.dx$, and $\int_{-L}^{L} f(x) \sin\frac{n\pi x}{L}.dx$. The intervals (-L, L) delineated the boundaries of the period such that the ordinates of the periodic function corresponded to the equally spaced abscissas, $\chi_0 = -L, \chi_1, \chi_2, \chi_3 \ldots, \chi_k = L$. The spacing used gave $t_n = .01$ secs. Since the time for the period was 6.5 seconds this enabled 650 data points per period to be used for the transform.

Correlational Analysis

Crosscorrelation functions and intertrial correlation matrices were used in this present study. A Pearson product-moment correlation (γ) was used to calculate the relationship between variance profiles. The 650 variance scores that were calculated from data sampled every 10 milliseconds throughout the movement sequence were used as the sample population.

Results and Discussion

The subject's (A.D.) movement variability decreased over the 10 blocks of trials in Experiment III (see Figure 15). This result was similar to those found in the previous experiments in this series. Specifically, a subject's response velocity during a specified pattern of movements becomes progressively more consistent within each block of trials as a result of increased practice. The consistency of movement witnessed in Experiment III was developed with full reportable knowledge of the stimulus composition. After the first block of trials A.D. was able to give a complete description of the composition of the stimulus. A.D. also reported making many corrective actions during the trials of Block 1. These corrections were in part responsible for the comparatively high variability score obtained during the first block of trials. It therefore appears that A.D. made full use of the stimulus course information gained during the initial trials in order to predict the movement of the stimulus marker in subsequent trials.

Within block crosscorrelation functions were computed between Trial 2 and Trial 7 for each block of trials (see Table 2). Trial 7 was used as the criterion set of scores and the velocity data from Trial 2 was advanced along a time line in intervals of 50 milliseconds. All correlation coefficients were maximum and positive when $\tau=0$. That is, there was no change in the time relationship between responses made *within* any block of trials. The within-block variance score was not representative of any phase relationship between responses made during one block of trials. A further feature of these results can be seen when a comparison is made between the crosscorrelation function of each block when $\tau=0$. The correlation coefficients between Trial 2 and Trial

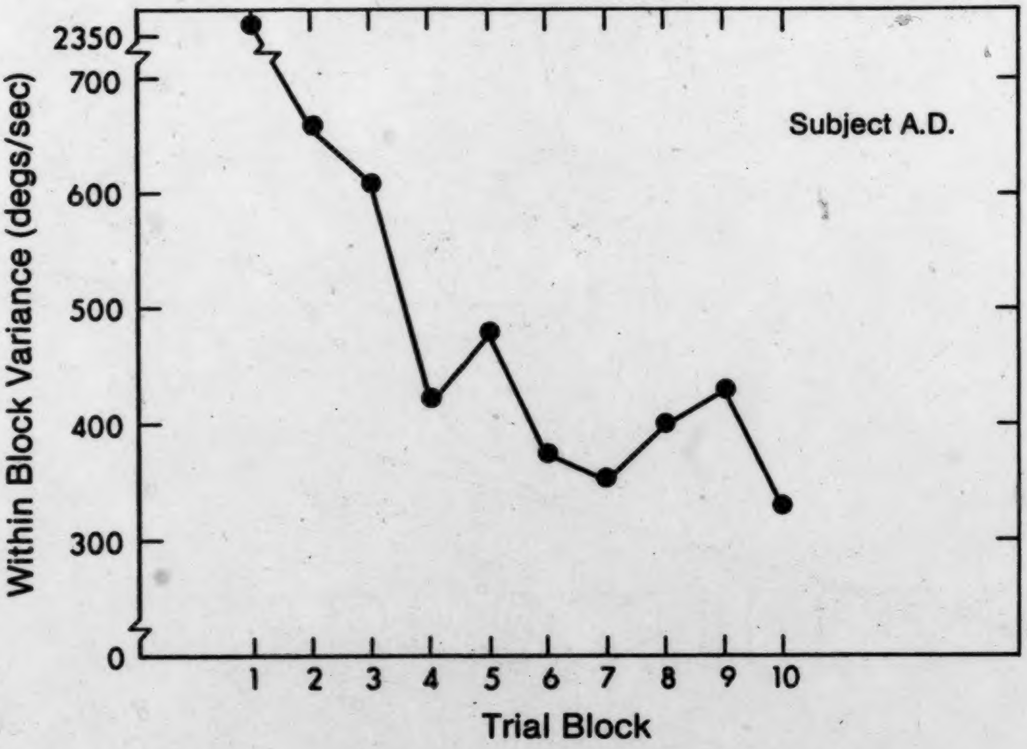

Figure 15. Average within block variance for response velocities taken during Experiment III for subject A.D.

Table 2

Within Block Crosscorrelation Functions for Movement Velocity of Responses

Block	$\tau=0^a$	$\tau=.05$	$\tau=.10$	$\tau=.15$	$\tau=.20$	$\tau=.25$
1	.92	.90	.87	.82	.77	.71
2	.92	.92	.90	.87	.82	.76
3	.90	.84	.77	.68	.59	.49
4	.98	.98	.97	.95	.90	.84
5	.98	.97	.93	.88	.80	.72
6	.98	.97	.94	.89	.82	.75
7	.98	.97	.95	.90	.87	.76
8	.99	.98	.97	.92	.85	.77
9	.99	.98	.86	.91	.85	.78
10	.99	.97	.91	.86	.80	.73

Note. Trial 2 and Trial 7 were used for the two sets of scores with Trial 7 as the criterion set.

[a] Time advance in seconds.

7 early on in practice (Blocks 1, 2, and 3) were lower than those obtained later in practice (Blocks 4 through 10). This is further evidence to support the thesis that during practice on a skill in which the environment is predictable a subject displays an increasingly narrower distribution of responses.

The distribution of response variance[†] throughout the movement pattern is shown in Figure 16. It can be seen that the areas of high variability correspond with periods of maximal velocity. This initial observation was confirmed when correlation coefficients were computed between velocity variance scores and mean velocity scores for each block of trials (see Table 3). A high negative correlation was found for all blocks except Block 1.[††] Indications were, that during any movement within the sequence, the subject was more variable when the velocity was approximately zero. However, upon closer inspection of individual movements the areas of highest variability appeared to occur during periods of maximal rate of change of velocity ($\frac{d\theta^2}{dt} \rightarrow$ maximum). The highly consistent phases of the movement were made during periods of maximum velocity ($\frac{d\theta^2}{dt} \rightarrow 0$). Figure 17 represents movement velocity graphs for Block 2, 4, 8, and 10. These graphs were drawn from movement velocity data taken over a single movement within the movement sequence. The sample movement that was used can be seen in Figure 14 and was described as a long movement, specifically the second long movement in the sequence. Also displayed on the graphs in Figure 17 are the standard deviations around selected periods of the movement. The

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[†] Variability of movement velocity was used as a measure of consistency.

[††] After viewing the variability profiles of Block 1 it appears that the subject was equally variable throughout the movement sequence.

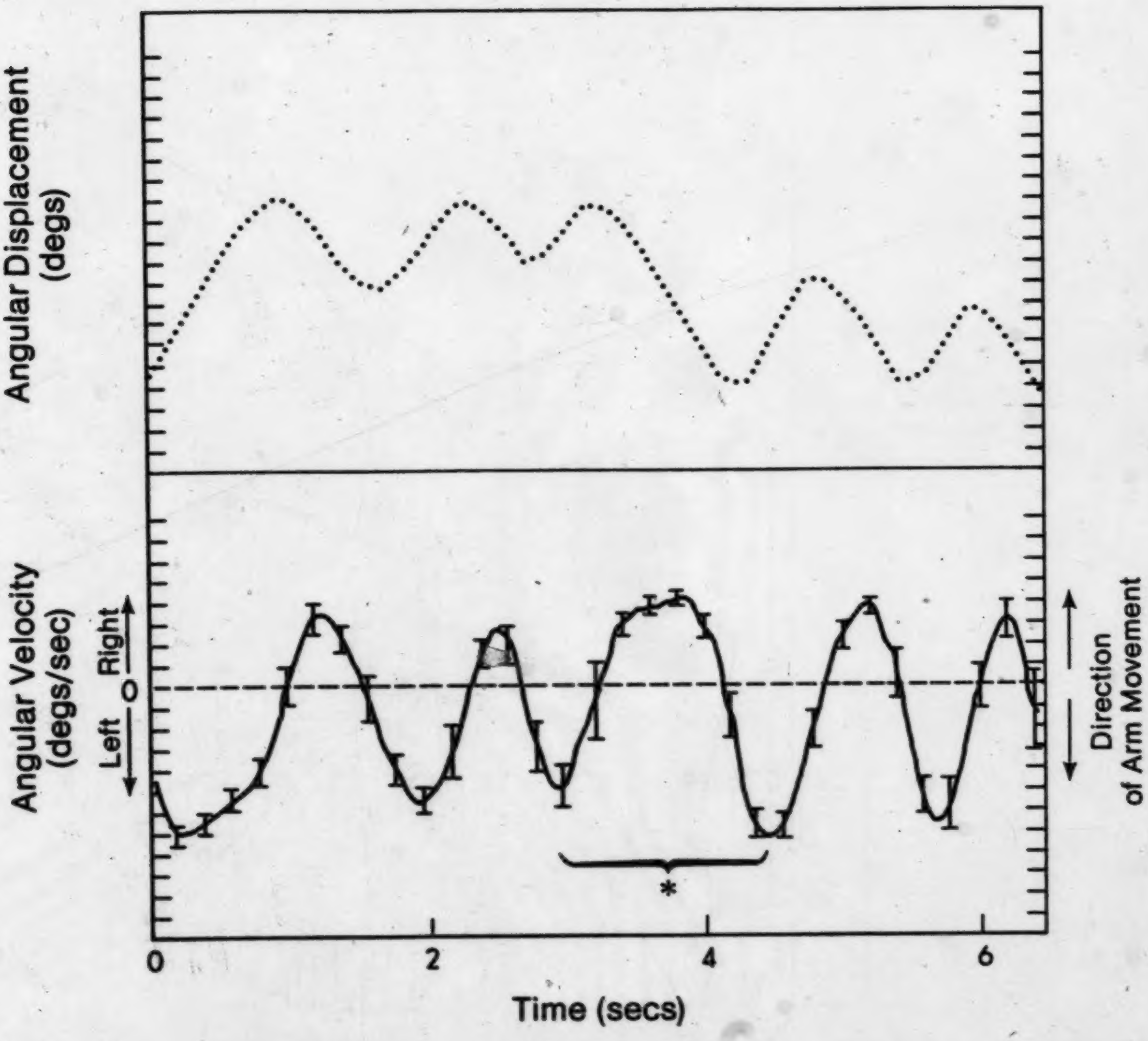


Figure 16. Angular Displacement and Angular Velocity curves for responses made during Block 10. The vertical lines through the velocity curve are the within block standard deviations for that point in time.

* See Figure 17 for detailed investigation of this move.

Table 3

Correlation Coefficients between Movement

Velocity Variance and Mean Velocity

Block	1	2	3	4	5	6	7	8	9	10
$\gamma_{(\sigma^2,\ \bar{X})}$	-.10	-.57	-.68	-.60	-.52	-.47	-.59	-.72	-.67	-.57

Note. The mean movement velocity for each block was correlated with the variance profile for each block (n=650).

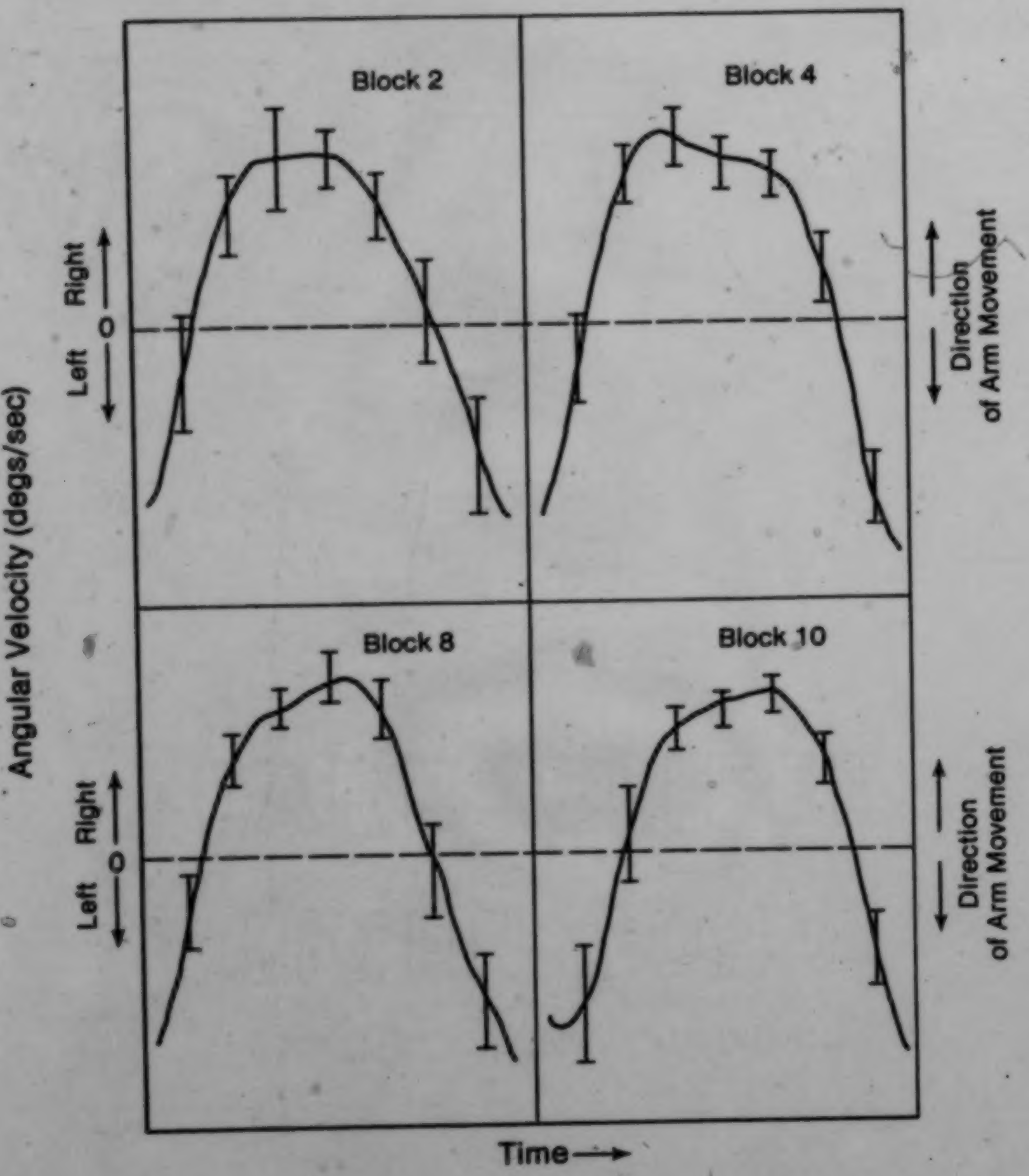


Figure 17. The distribution of variance around the long movement in the movement sequence. Vertical lines are the within block standard deviations at that point in time.

large deviations around periods of acceleration and deceleration were maintained throughout the experiment, whereas the comparatively smaller deviations around the periods of maximum velocity decreased as the experiment proceeded. The overall decrease in response variability over trials therefore, appears to be due mainly to a decrease in variability around the mid-part of each movement $(\frac{d\theta^2}{dt} = 0)$ within the movement sequence.

Component frequencies of the responses made by A.D. while tracking are illustrated in Figure 18. These responses, that were submitted to analysis by Fourier transform, showed a tendency to approximate the stimulus signal. This finding is contrary to the results of the first two experiments, wherein the constant velocity ramp track was found to be a poor approximation to human tracking behaviour. The amplitudes of the fundamental harmonics for the responses made during the selected trial blocks (Blocks 2, 4, and 8) were greater than the fundamental harmonic of the stimulus signal. This difference in amplitude remained relatively constant throughout the experiment. However, the amplitude of the fifth harmonic approached the stimulus value as practice continued. Due to the reflective nature of the stimulus signal, there were no even harmonics present in frequency analysis. Therefore the even harmonics decreased in amplitude and were relatively undetectable by Block 10. Corrections made by A.D. were probably responsible for this response remnant. The period for the response function remained stable throughout the experiment $(.99 \text{ rad/sec} \leq \omega \leq 1.0 \text{ rad/sec})$. This stability was expected since the stimulus paced the response output.

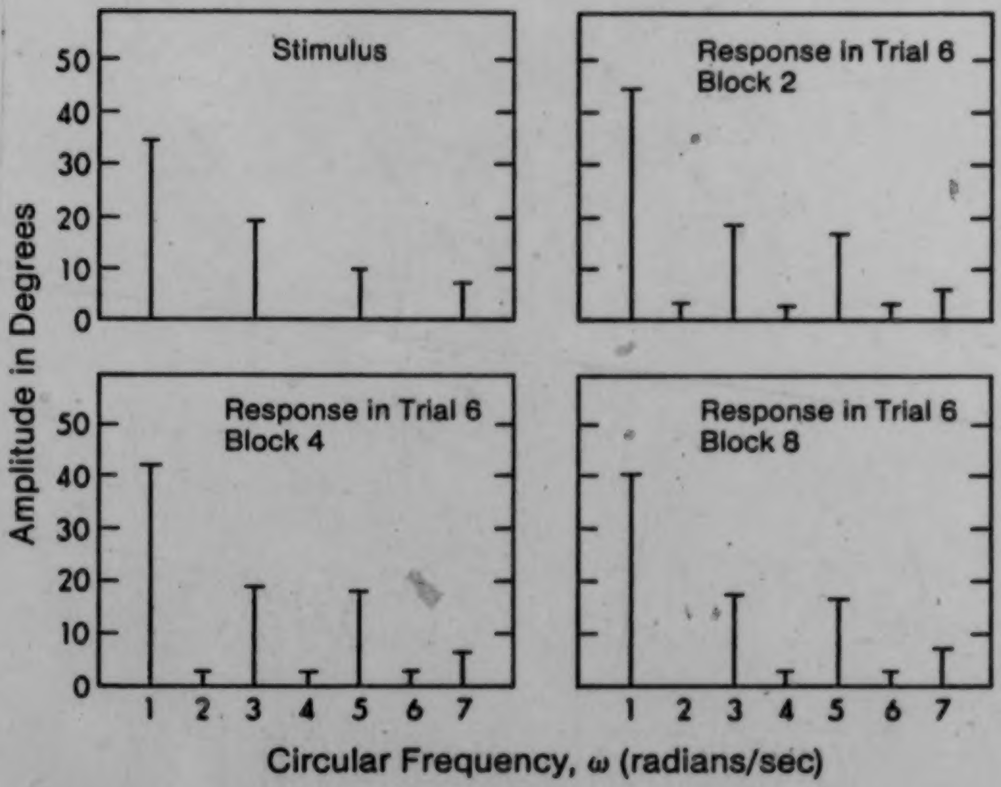


Figure 18. The component frequencies of the stimulus and the responses made to this stimulus signal over trial blocks.

EXPERIMENT IV

The use of consistency as a worthwhile measurement of performance has been criticized by Poulton (1974, p. 49). His objections were that consistent performance may not be equivalent to good performance, for example, technique errors may be displayed by the performer with increasing consistency. The within-subject variance measure used in Experiments I, II and III therefore may not have reflected an improvement in performance as measured against an experimentally defined criterion. The present experiment was designed to validate the proposed consistency measure and answer Poulton's objections to consistency as an indicant of skilled performance.

The relationship between the variability of repeated responses and the errors produced by those responses was investigated. The task used in this study was a pursuit tracking task. This task allowed the subject to perceive his produced error visually, in contrast to the blind tracking task[†] used in the previous experiments. Consequently the change in task allowed the subjects to utilize a variety of information including that related to tracking error. The movements the subjects initiated to correct alignment errors were expected to reduce error while increasing variability of movement velocity. However, despite this increased awareness of subjective error it was hypothesized that the within-subject variance would decrease over trial blocks.

[†] During the blind tracking task there was no visual indication of the subject's response displayed on the CRT.

Method

Subjects

Five male graduate students in full time attendance at the University of Alberta were used as subjects in this experiment. They ranged in age from 23 years to 30 years and all wrote with their right hand.

Apparatus and Task

Due to the nature of the task in this experiment (pursuit tracking) several changes were made to the apparatus that was used in the previous studies. Two independantly controlled markers were displayed on the CRT. A varying voltage output from the D/A channel of the computer controlled the stimulus signal. The subject's response involved moving the controlled element (radial arm) through an angle of 132 degrees. The controlled element pivoted around a 20 K.Ohm, one turn, ganged potentiometer, which was in turn connected in parallel to a 5-volt DC power supply. The response movement was therefore converted to a voltage change. This voltage change was utilized for two purposes. Firstly, it was used to drive the stimulus signal and secondly, the change in voltage was converted to a digital value and stored via the A/D converter channel of the computer. The ganged potentiometer completed these two circuits. A schematic respresentation of the electrical circuit is shown in Figure 19.

The stimulus marker, 900mm high and 75mm wide, was centred in the upper half of a 27 inch (64.8 cm) display screen (CRT). The response marker, situated immediately below the stimulus marker, was 100mm high and 50mm wide. The maximum possible displacement of the stimulus marker was 22 cm of horizontal movement. A zero order (position)

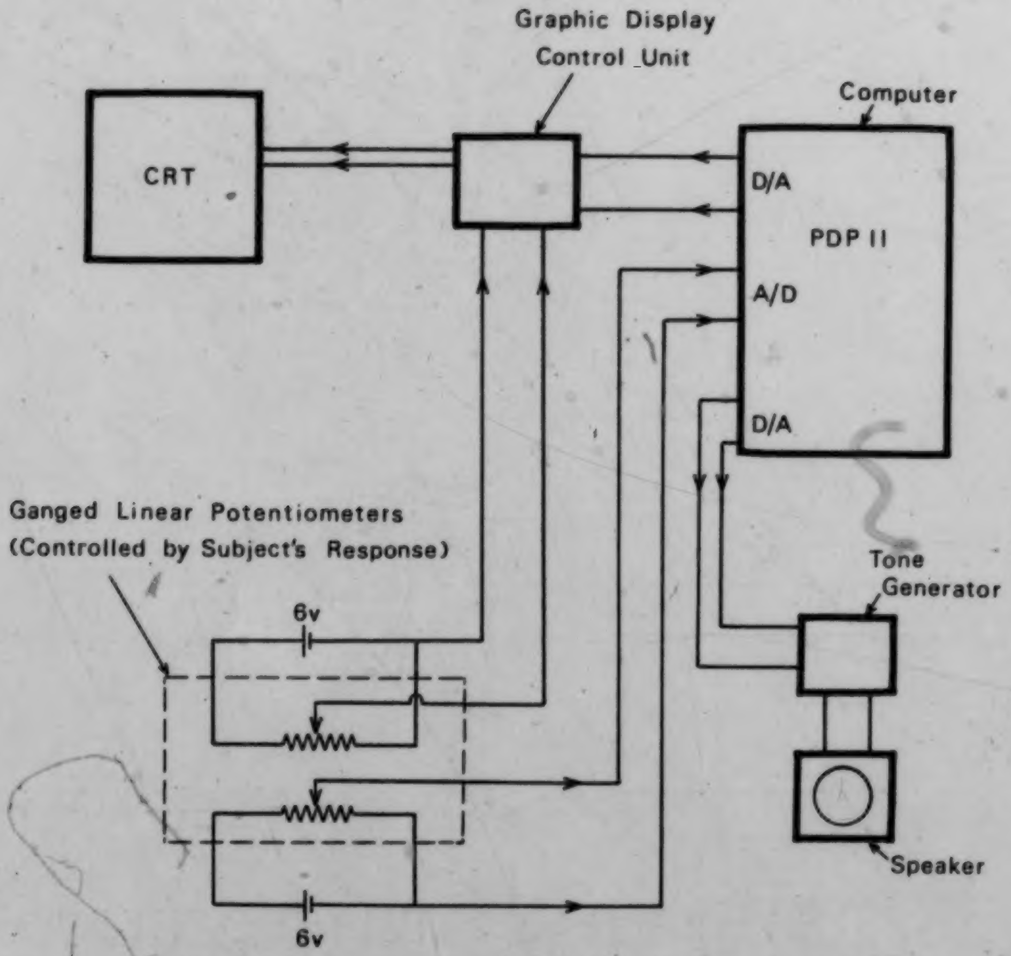

Graphic Display
Control Unit
Computer
CRT
D/A
PDP II
A/D
D/A
Ganged Linear Potentiometers
(Controlled by Subject's Response)
6v
Tone
Generator
Speaker
6v

Figure 19. Electrical circuit of the pursuit tracking apparatus.

control system, that equated six degrees of response movement with 100mm of response marker displacement, was used.

As in the previous experiments the subjects were seated in front of the apparatus (see Figure 1) with the palm of their right hand over the handle of the controlled element. A screen was mounted in front of and above the subjects right arm such that the subjects could not see the movements of their arm. In addition, the lights in the testing laboratory were dimmed. This was done to prevent distracting reflections being reflected from the screen.

The study spanned a period of 10 days with each subject completing one experimental session (block of trials) per day. Each block of trials consisted of a training phase followed by a testing phase. During the training phase, the subjects were required to track (pursuit) a sine wave for 20 cycles. The amplitude and frequency of this sine wave was equivalent to that of the fundamental of the composite sinusoidal waveform used in the testing phase. The training phase was undertaken solely to familiarize the subjects with the task. A 10 second delay followed the training phase. This delay was followed by a long tone (duration 3 seconds) which signalled the commencement of the first of seven trials. The subjects were asked to track a composite sinusoidal wave[†] ($f(t) = \frac{A_0}{2} + Cn \sin\omega t + \frac{Cn}{2} \sin 2\omega t + \frac{Cn}{4} \sin 4\omega t$) for 15 cycles; each cycle lasted a period of 2.564 seconds. The subject's response to the eighth cycle of this periodic waveform was sampled at a rate of 1000 data points per second. Approximately 2600 data points were sampled and stored for each trial. Between each of the seven trials the subjects were given a 10 second rest. After each block of trials the subjects were informed of how much error they had accumulated over the seven trials.

[†] Graph of this waveform can be seen in Figure 20.

A PDP 11/10 computer controlled all aspects of the experiment including signal output, data acquisition and data storage. Immediately following each block of trials the error scores, variance scores and correlational matrices were calculated from the stored raw data. Additional data was obtained from the subjects after Trial Blocks 1, 5 and 10. This extra requirement had the subjects draw from memory, the stimulus waveform in as much detail as was possible.

Data Analysis

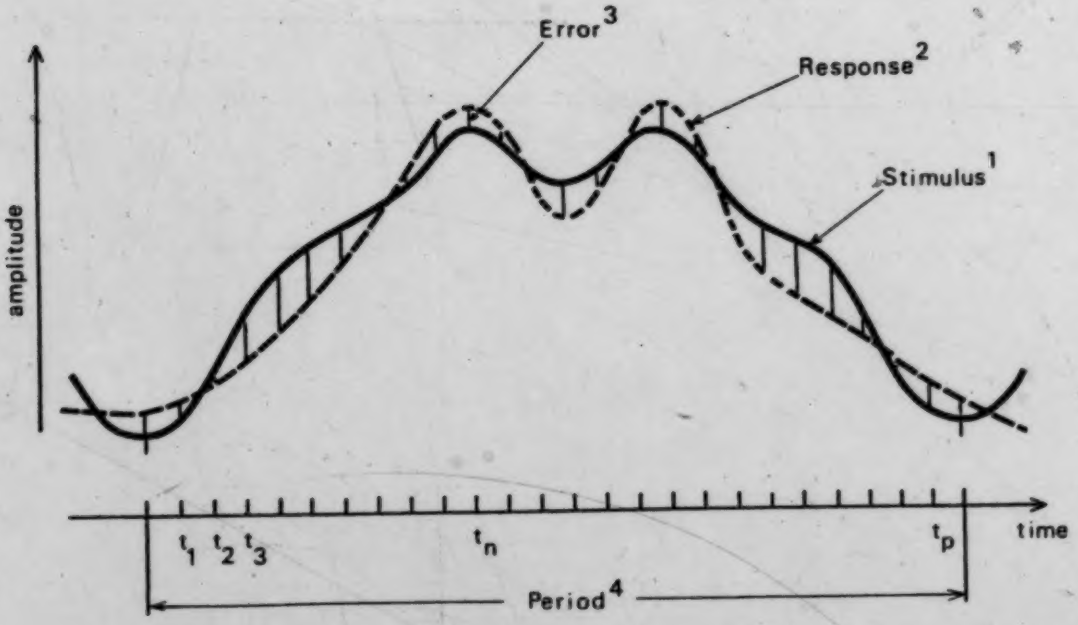
Within-Subject Variance

The variability of the subject's movement velocity was calculated within each block of seven trials for data samples taken during the eighth cycle in each trial. During this cycle, data samples were taken at millisecond intervals over a period of 2.6 seconds. The velocity curves derived from these data were superimposed and for each time interval a standard deviation (SD) of the seven velocities was obtained. This produced 2600 SDs for one block of trials. The average of these SDs was taken as an index of within-subject variance for that specific block of trials. The 2600 SD scores were stored and used in later calculations.

Root Mean Squared Error (RMSE)

The computation of the RMSE scores are shown in Figure 20. Poulton (1974, p. 35) defines RMSE as being $\frac{\sqrt{\sum_{n=p}^{1} e^{2}{}_{nm}}}{p}$ where e_{nm} is the error at time interval t_n for trial m, and p is the number of intervals that the error is sampled over during the period. To obtain an error score for each block of trials the RMSE for each trial were summed over the seven trials. This computation produced an error score for each block of trials that was averaged over the period and summed over the seven trials, hence $RMSEp = \sum_{m=7}^{1} \frac{\sqrt{\sum_{n=p}^{1} e^{2}{}_{nm}}}{p}$. Because the within-subject variance score reflects the variability of repeated responses at specific time intervals of the period between trials, another error score was derived. This RMSE score resulted from the averaged error of the seven trials at a specific time interval and was summed over the period of the cycle. Therefore, $RMSEt = \sum_{n=p}^{1} \frac{\sqrt{\sum_{m=7}^{1} e^{2}{}_{nm}}}{m}$. The RMSEt was therefore calculated from 2600 data points that were equivalent in

Root Mean Squared (RMS) Error Scores.


Error ^{3}
Response ^{2}
Stimulus ^{1}
amplitude
time
t_1 t_2 t_3
t_n
t_p
Period ^{4}

1. Stimulus is given by $f(t) = \frac{A_0}{2} + C.\sin\omega t + \frac{C_1}{2}\sin 2\omega t + \frac{C_1}{4}\sin 4\omega t$

2. Response for Trial m (7 trials per block) $\therefore m = 1 \rightarrow 7$

3. Error at time t_n (Trial m): e_{nm}

4. Period (one complete cycle) = 2·564 secs. $\therefore p = 2564$

$$\text{RMSE}.p = \sum_{m=7}^{1} \sqrt{\frac{\sum_{n=p}^{1} e_{nm}^{2}}{n}} \qquad \text{RMSE}.t = \sum_{n=p}^{1} \sqrt{\frac{\sum_{m=7}^{1} e_{nm}^{2}}{m}}$$

Figure 20. Description of the stimulus signal and an explanation of how the error scores were derived for Experiment IV

sampling time to the SD scores used to calculate the within-subject variance score. This profile of error scores and variance scores allowed a judgement to be made regarding the within-block error and within-block variance. More specifically, it was possible to determine independantly throughout the period where the subjects were variable and errorful.

Correctional Analysis

A Pearson product-moment correlation (γ) was used to calculate the correlation coefficients used in this experiment. An interblock correlation matrix was compiled for variance scores and error scores that were obtained during each block of trials. Also the correlation coefficient between the variance and error profiles was calculated for each block of trials. All calculations were completed for individual subjects.

Results and Discussion

Variance

As the number of trials increased subjects experienced a corresponding reduction in their movement variance as measured by the SD of the movement velocity (see Figure 21). This finding is in agreement with the results of the previous three experiments. During the earlier trial blocks the subjects displayed large individual differences in variance scores. However, late in practice (Trial Blocks 8, 9 and 10) the subjects recorded similar variance scores and similar trends in performance. Further supporting evidence that subjects became more consistent as a result of practice is given in Appendix D. The within-block correlation matrices of velocities for Block 1, 5 and 10 for each subject are shown in this appendix. It can be seen that the correlation coefficients within these matrices increased as the subjects continued practice on the tracking task. Movement velocities made by subjects in pursuit of the stimulus in Trial Block 10 were more tightly distributed than those movements made during any of the preceding trial blocks. Additional confirmation that subjects became more consistent in their movements later in practice is shown in Table 4. This correlation matrix was calculated using mean[†] variance profiles derived from each block of seven trials. The correlation coefficients between Blocks 8, 9 and 10 are higher than the coefficients between other trial blocks. It appears that the variance profiles stabilized as the number of trials increased. That is, the subjects variability within a movement sequence became increasingly more predictable as they learned the move-

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[†] The variance profiles were averaged across subjects.

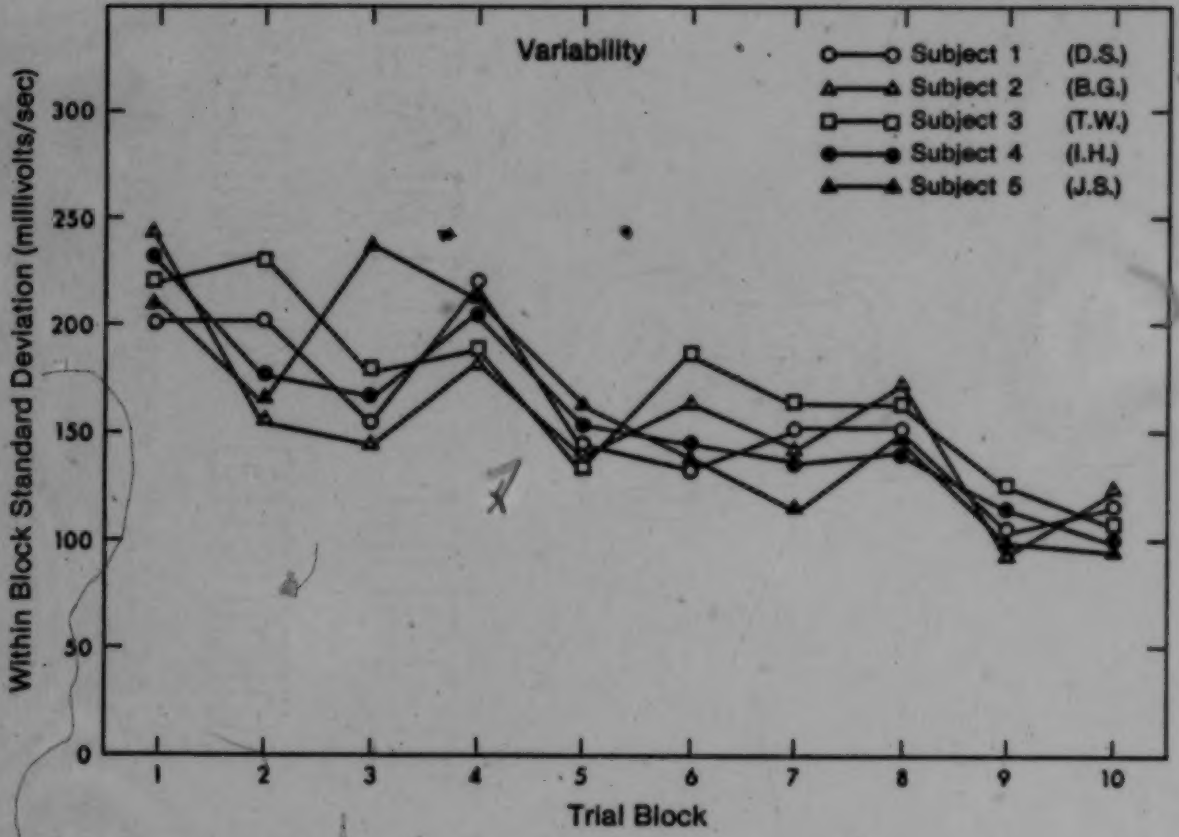

Figure 21. Within subject variance scores for the 10 trial blocks. The standard scores are taken as a consistency index ofthe movement velocity during Experiment IV.

Table 4

Mean, Standard Deviation and Correlation Matrix for the Within-Subject Variance Scores of each Block of Trials.

Block	Mean	SD
1	226	53
2	187	42
3	180	46
4	203	46
5	149	29
6	157	36
7	149	27
8	158	27
9	111	37
10	118	33

Block	1	2	3	4	5	6	7	8	9	10
1	---	.51	.64	.56	.55	.37	.18	.47	.41	.50
2		---	.69	.36	.56	.53	.33	.50	.45	.54
3			---	.54	.70	.62	.48	.62	.66	.71
4				---	.54	.32	.31	.27	.38	.41
5					---	.45	.32	.44	.57	.58
6						---	.61	.58	.58	.70
7							---	.53	.59	.59
8								---	.66	.68
9									---	.80
10										---

Note. The within-subject variance scores were averaged across five subjects.

ment, even though the overall variance[†] within the movement sequence decreased.

Error

The root mean squared error scores that were averaged over the period (RMSE p) are shown in Figure 22. As expected there was a general decline in errors as a result of practice. All subjects showed a large reduction in tracking error before Block 5, after which their performance as measured by RMSE reached a plateau. There also appeared to be wide individual differences in error scores on early trials while the results of later trials reflected more tightly distributed scores.

Calculation of the RMSEt data made it possible to obtain an error profile for the sampled movement (eighth cycle in each trial). All subjects showed similar error profiles and the profiles from Block 1 and 10 are shown in Figure 23. It can be seen that there were three main areas of error production. Two of these areas were in the change of speed without reversal, located along the sides of the waveform (see Figure 20). One further position along the track where subjects were most errorful was at the second peak of the waveform. When the actual response records were examined it was clear that all subjects in all blocks of trials undershot this reversal. While the whole profile decreased with increasing practice, it was notable that a large reduction in RMSEt was due to the subjects' tracking improvement at the positions of change of speed without reversal. By Block 10 all subjects (with the exception of B.G.) were aware of this slight nuance

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[†] The within-subject variance decreased as the number of trials increased (see Figure 21).

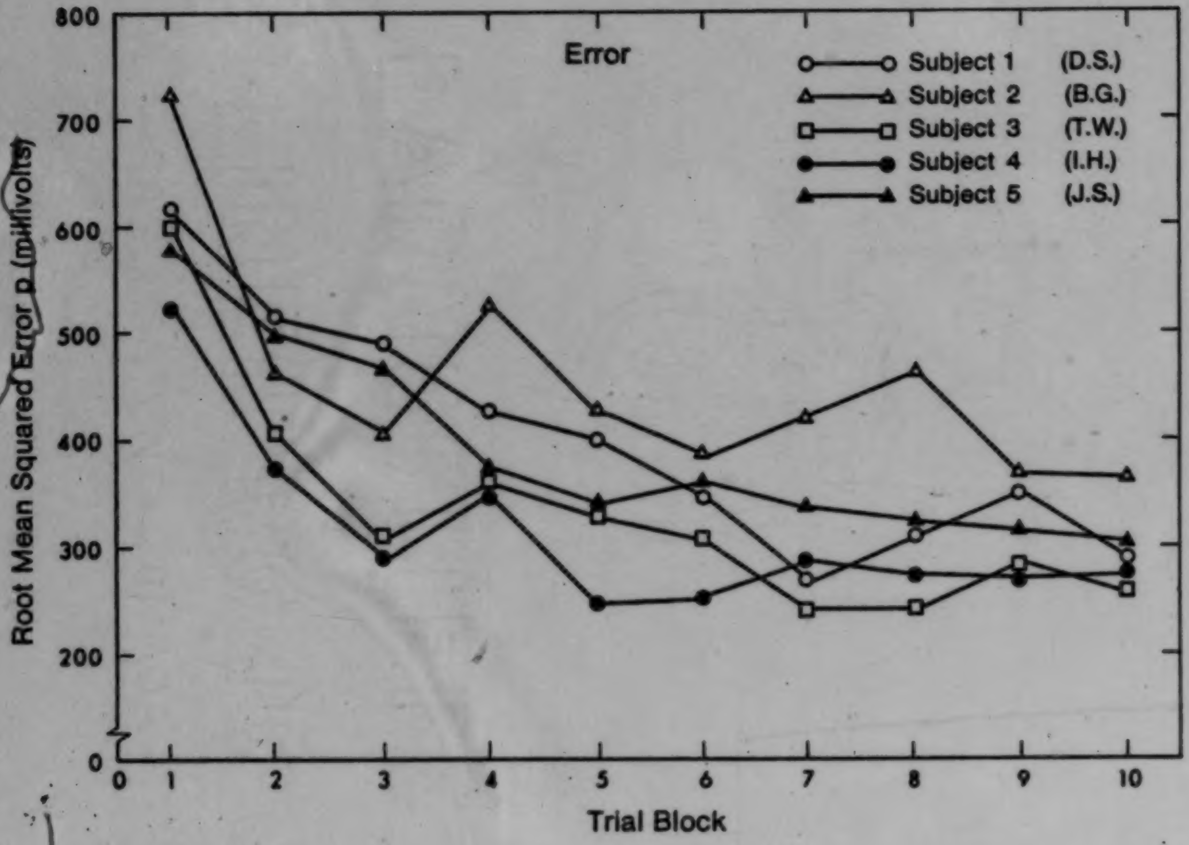

Figure 22. Root mean squared error for the 10 trial blocks of Experiment IV. The RMSE is averaged over the period of the eighth cycle of each trial and summed over the seven trials of each block.

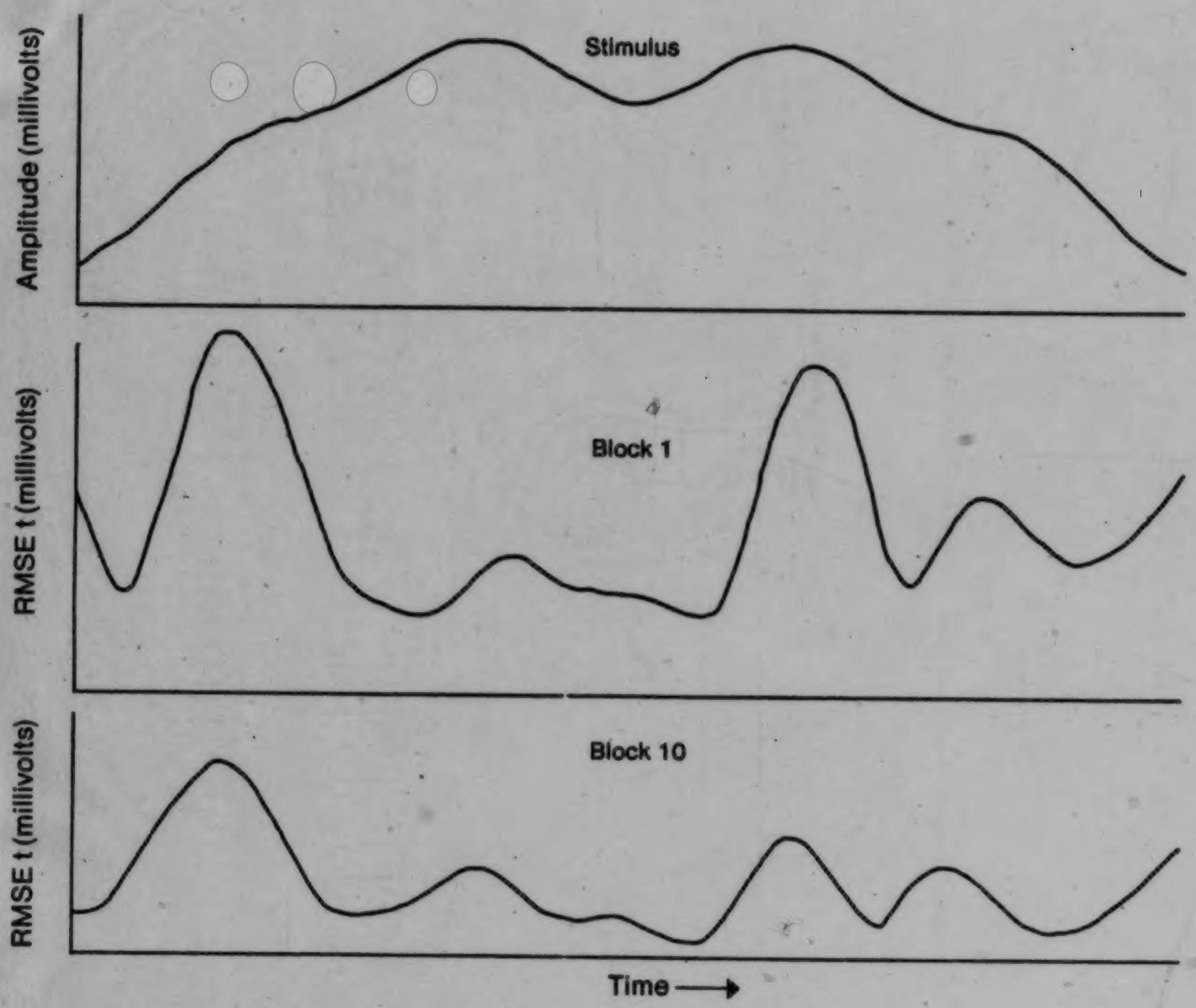

Figure 23. The average RMSE t profiles for Blocks 1 and 10 compared to the stimulus.

in the track. The freehand sketches completed by the subjects after Blocks 1, 5 and 10 reflect this awareness of pattern detail quite well. The reproductions from these drawings can be seen in Figure 24. It appears that after Block 5 the subjects were aware of changes in speed of the track but could not accurately record them. After the last testing session all subjects, with the exception of B.G., sketched at least one change of speed correctly. While the subjects were drawing the stimulus track it was interesting to note that on every occasion, all subjects had to move their arm or even go back to the equipment and move the controlled element before they could produce a representation of the stimulus.

The interblock correlation matrix for RMSEt averaged across subjects is shown in Table 5. The matrices for individual subjects are presented in Appendix E. The groups of coefficients that are of interest have been demarcated. The coefficients for Blocks 8, 9 and 10 are high and positive, which suggests that the subjects were making errors in the same place along the track. However, the degree of association between the RMSEt of the first three blocks and the later blocks is not as high. Along with a stabilization of variability of performance that was discussed earlier, subjects also appear to have localized their error production. Although the whole profile of errors "flattened out" the lumps and bumps that remained must be well defined and relatively repeatable for such high correleation coefficients to have been obtained.

Comparison of Error and Variance

A correlation coefficient was computed between the RMSEt profiles and the within-subject variance profiles for each subject on every

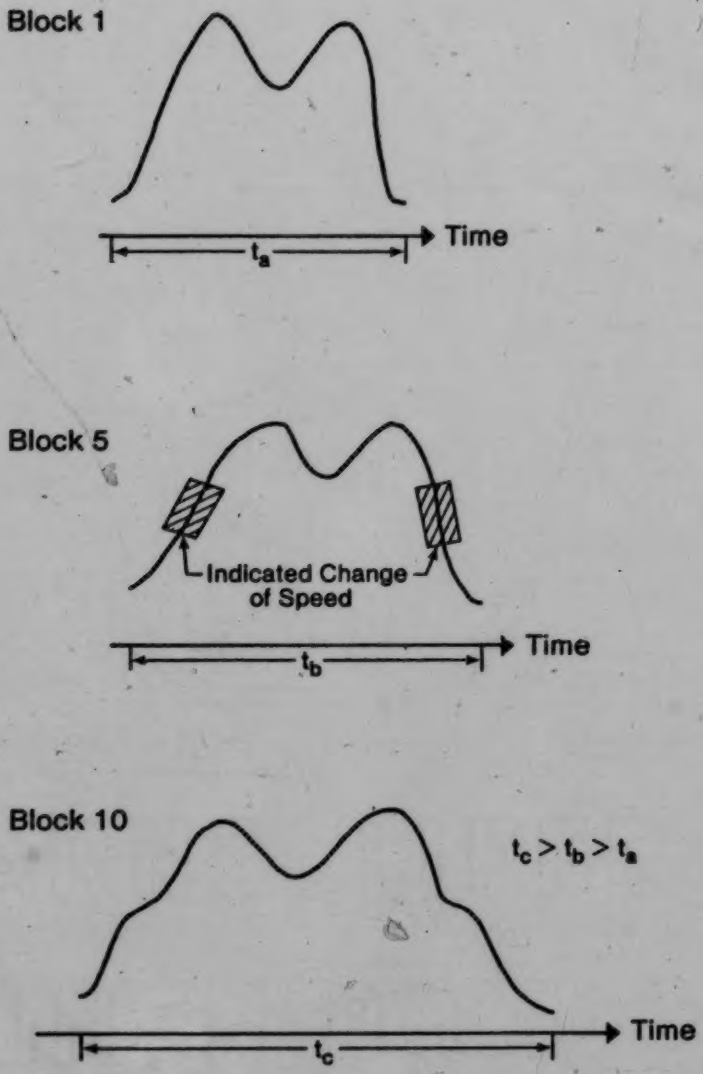
Block 1
Time
t_a
Block 5
Indicated Change of Speed
Time
t_b
Block 10
$t_c > t_b > t_a$
Time
t_c

Figure 24. An approximation of the features that were evident in the subjects' freehand sketches of the stimulus after Trial Blocks 1, 5 and 10.

Table 5

Mean, Standard Deviation and Correlation Matrix for the RMSEt of each Block of Trials.

Block	Mean	SD
1	80	36
2	57	26
3	51	21
4	51	25
5	44	20
6	43	16
7	39	18
8	41	20
9	39	20
10	37	19

Block	1	2	3	4	5	6	7	8	9	10
1	---	.92	.90	.85	.89	.79	.78	.79	.79	.83
2		---	.96	.93	.93	.88	.86	.85	.88	.88
3			---	.93	.92	.85	.86	.86	.88	.89
4				---	.96	.92	.96	.96	.97	.94
5					---	.92	.92	.94	.95	.94
6						---	.91	.91	.92	.87
7							---	.99	.99	.95
8								---	.99	.97
9									---	.96
10										---

Note. The RMSEt values used were averaged across the five subjects.

block of trials. The results of this computation are shown in Table 6. The relationship between variability and error was examined through this analysis. There appears to be no relationship between the profiles of variability and the profiles of RMSEt. All correlation coefficients approach zero. This is one indication that the assigned error measurement used and the variance of movement velocity describe different aspects of the subjects' performance. Although the two indicants of skilled performance, consistency and error, do not seem to be directly related they both follow the same general trend. That is, as the number of trials increased on a tracking task, subjects reduced their movement variability in addition to reducing their error scores.

A comparison of the three measurements used, SD of movement velocity, RMSEp and RMSEt can be seen in Figure 25. The RMSEp and RMSEt scores virtually parallel each other which was to be expected because of the mathematical derivation of RMSEt. The use of RMSEt as one error measure that can readily be compared to the proposed variance measure appears therefore to be justified. Figure 26 is a plot of the RMSEt scores per block against the SD of movement velocity scores for each subject. The scattergram was compiled therefore from 50 pairs of co-ordinates and a regression analysis was completed on the data. This analysis revealed a correlation coefficient of .67 from which a significant $t = 6.25$ ($\alpha = .005$) was obtained. The fact that the SD of movement velocity within each trial block decreased despite the subjects' increased awareness of perceived error[†] is vindication of the proposed variance measure's relevance in this type of learning study.

[†] Use of pursuit tracking as opposed to blind tracking.

Table 6

Correlation Coefficients of RMSEt Profiles

and SD Profiles for each Trial Block (Expt. IV)

	TRIAL BLOCK									
SUBJECT	1	2	3	4	5	6	7	8	9	10
1. D.S.	.27	.15	-.10	-.01	-.11	-.08	-.17	-.20	-.05	.01
2. B.G.	-.13	-.03	-.11	-.09	-.25	-.08	-.11	-.09	.10	.05
3. T.W.	-.16	-.19	.11	.19	.08	-.04	.02	-.04	.25	-.20
4. I.H.	-.10	-.04	.08	.36	.12	.13	-.09	.05	-.17	-.12
5. J.S.	-.23	-.05	.11	-.14	.01	-.12	-.01	.02	-.01	-.05

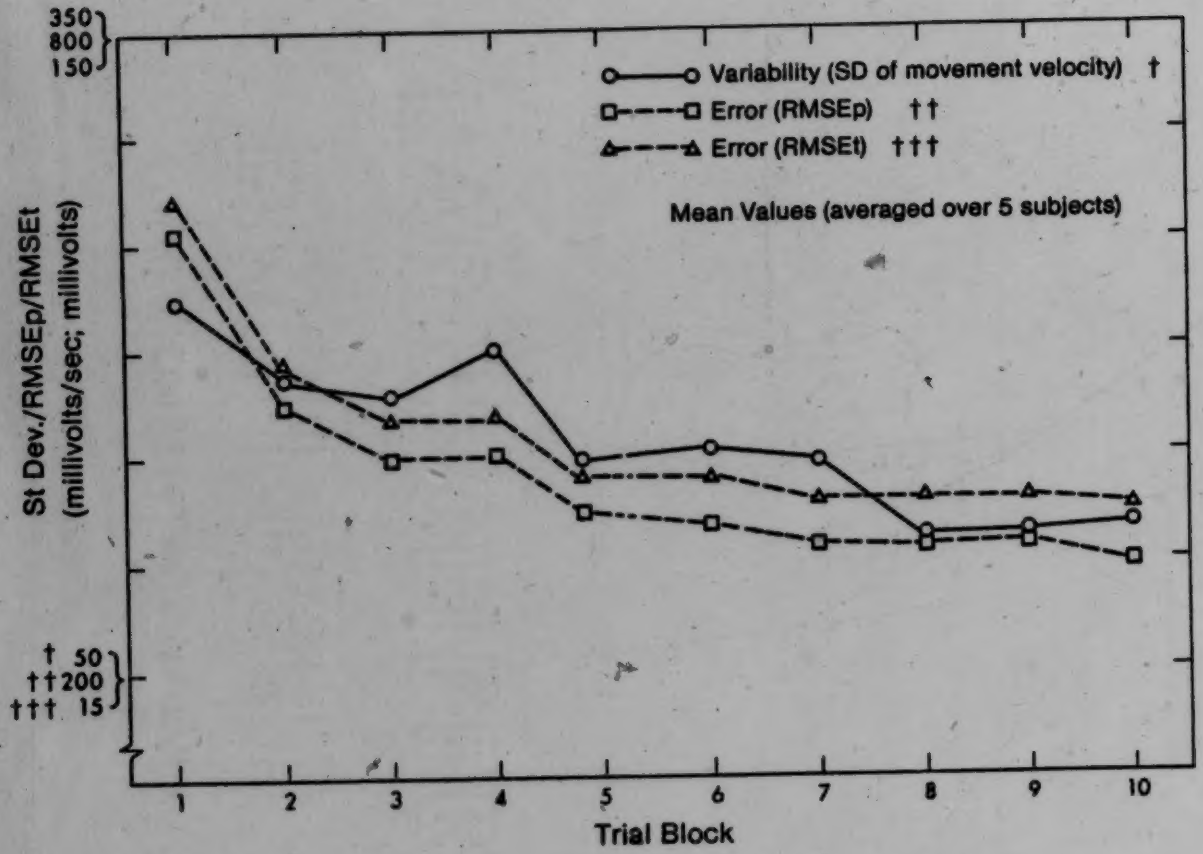

Figure 25. Comparison of mean error measures and mean variance measures. The RMSEp, RMSEt and SD of the velocity are graphed on the same axis.

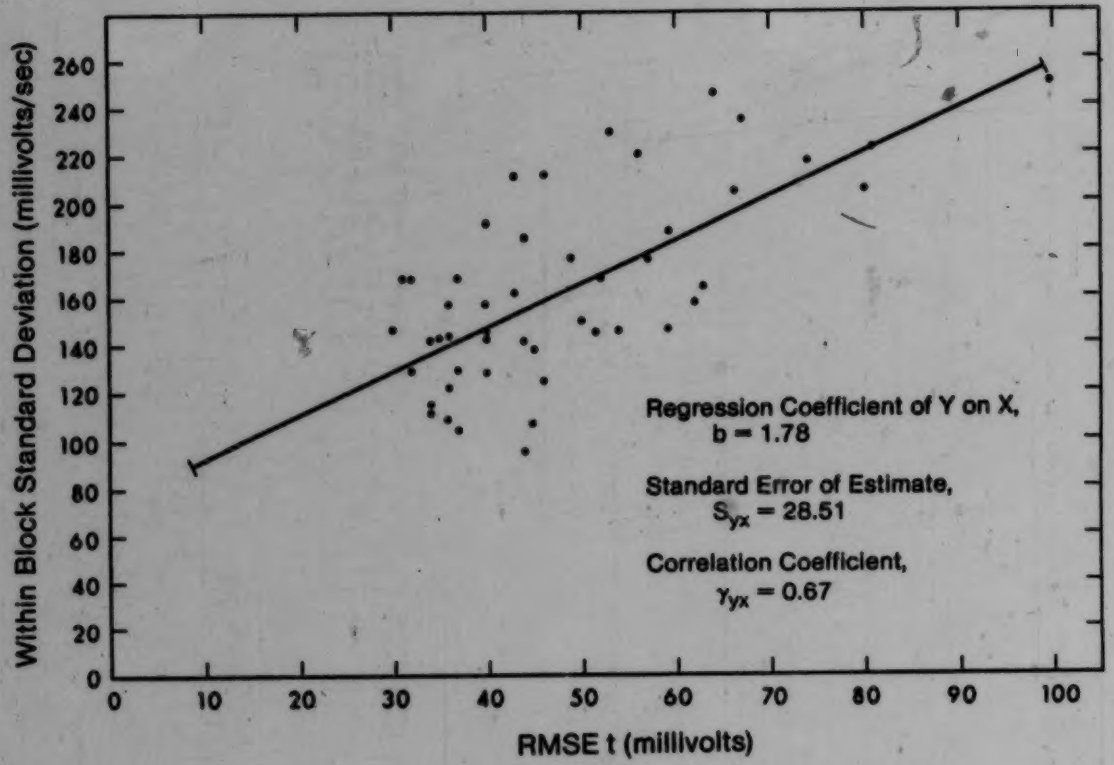

Figure 26. Plot of RMSEt scores and SD scores. Each of the five subjects' 10 pairs of scores are plotted. A regression line and correlation coefficient was calculated from these data pairs.

In summary, as the subjects became less errorful on their tracking task they also became less variable in their movements. However, changes may occur either independently or in unison. Although the averaged graph in Figure 25 shows concurrent trends in both error and variance, a more detailed indication of the relationship between these two measures can be seen by comparing Figures 21 and 22. These figures map individual performance over the 10 trial blocks. For example, subject 5 (J.S.) reduced his error during Block 3 but increased his variability. A closer inspection of these graphs will underline the fact that the trend of the individual variance score does not mirror the error score. Subject 2 (B.G.) has a comparatively low variance score (indeed, his variance score on Block 9 was the lowest recorded) while maintaining the highest error score on almost every block. This observation would lead to the suggestion that variability cannot be taken as a lone indicator of performance, and could be taken as a partial acceptance of Poulton's criticism. However the need to more fully describe the response made by a subject in a learning study has been realized. There have been indications for instance that subjects who do not reduce error significantly from one testing session to the next may be accepting a certain bandwidth of error in order to decrease their movement variance. Also, it may be that subjects, in an attempt to change their level of performance with respect to perceived error, change their pattern of movement and hence increase their movement variance.

EXPERIMENT V

The previous four experiments were designed to investigate several indicants of skillful performance and their interrelationships. The task that was used as the vehicle for these studies was the perceptual motor task of tracking. As subjects practiced on both pursuit and blind tracking tasks several aspects of their performance were assessed. Firstly, as a subject learned the tracking task, he not only became less errorful, but also more consistent in the movement patterns he used to reduce this error. Secondly, there was evidence from cross-correlational data that the subjects changed their strategy during learning. This resulted in the response being advanced in time. It appeared that early in learning subjects adopted what Zohar (1974) termed a "wait and move" strategy, lagging behind the stimulus by approximately one reaction time. As subjects became more skillful at tracking and also more knowledgeable about the stimulus course, they responded on the basis of predicted future states of the stimulus. Poulton (1952) termed this type of prediction "perceptual anticipation".

During Experiments II, III and IV the subjects had full reportable knowledge of the stimulus signal's pattern of movements. This knowledge was gained following a limited number of trials at the task. It appeared that as subjects improved at the tracking task they also developed a more detailed memorial representation of the stimulus course. However, the only evidence to substantiate this observation has been the subjects' introspections and post-experimental, freehand sketches of the stimulus course. Therefore, the following experiment was undertaken to elucidate the development of a memorized control sequence that reproduces the learned response.

Several authors have made reference to a memorized pattern that has been generated by subjects during a tracking task. Magdaleno, Jex and Johnson (1970) have indicated that two factors are important to the development of this pattern generation process. These two factors relate to the level of learning that the subject has achieved and the frequency and periodicity of the stimulus signal. With a highly predictable waveform that has a centre frequency between .75 and 1.5 Hz the subject can generate his own movement pattern based upon prior tracking experience. Once the subject has detected the coherency in the stimulus signal, he then makes use of this information to generate a waveform of his own. He then attempts to synchronize his generated pattern with the desired input pattern. This description of the human operator's performance while tracking is closely aligned to the higher order control systems postulated by Pew (1974a). At this level of control, prediction and response programming become more prominent and the elementary servo mechanism[†] used to correct error is called upon less and less. Subjects can generate more complex patterned outputs and monitor the correspondence between the produced pattern and the desired pattern using a more sophisticated error detection mechanism.

Earlier investigations into the composition of memorized movement patterns have utilized a methodology termed "input blanking", where both the stimulus and response markers are removed from the display and the subject continues to produce the required movement pattern. In the present experiment subjects tracked (pursuit) a composite sinusoidal waveform, and after each trial the subjects had the input blanked. The removal of the visual display was done via a shaping technique that was employed with the express purpose of providing as little disturbance to the performer as possible. The subject could perceive both stimulus and response display markers during the earlier stages of the blanking trial. After approximately 15 seconds of pursuit tracking the response marker was removed, leaving only the stimulus marker visible.[†] This blind tracking task continued for a further 10 seconds until a tone cued the removal of the stimulus marker. After the stimulus was blanked the subject continued to generate the required response that was not influenced by any visual information for a period of seven seconds. A component frequency analysis was used to describe the composition of the produced response.

[†] Pew's model of hierarchical control systems is built upon a rudimentary inner loop control that is analogous to an elementary servo mechanism. When the signal to be followed is unpredictable then the system responds to perceived errors. This concept is drawn from the theory of feedback control and acts on changes in the environment and the results of the immediately preceding movement.

The stimulus waveform used in Experiment IV was again used in this experiment (see Figure 20). This allowed the conditions of Experiment IV to be replicated. Also the structure of the waveform was such that as the subjects' performance improved they became more aware of the detail inherent within the stimulus signal. For example, during Experiment IV the subjects were not aware of the change of speed without reversal along the sides of the waveform until after Trial Block 5. However, all subjects were able to sketch the stimulus signal in a generalized rudimentary form after Trial Block 1. Also, after the first session all subjects were reasonably confident that their sketches adequately described the stimulus. In the present experiment, it was expected that the subjects' memorial representation of the stimulus signal would become more detailed with practice. That is, as the subjects improve their performance at tracking, the pattern that they generate becomes more like that of the stimulus.

[†] This condition was the same as the blind tracking task used in Experiments I, II and III.

Method

Subjects

Two male (P.B. and R.P.) and two female (K.M. and S.R.) graduate students volunteered as subjects for this study. All four subjects wrote with their right hand and had not served in any previous tracking experiments. They ranged in age from 23 years to 30 years.

Apparatus and Task

The apparatus and task described in Experiment IV was used in this experiment, with the addition of an input blanking phase after each trial.

The experiment spanned a time period of 10 days, with the subjects completing one block of trials per day. At the commencement of each block the subjects tracked a sine wave for 20 cycles to familiarize them with the experimental task and environment. The subjects then completed seven trials, each was comprised of a regular tracking task followed by an input blanking task. The pursuit tracking task was identical to that described in Experiment IV. The subject tracked the stimulus waveform for 15 cycles with the response to the eighth cycle being sampled at a rate of 1000 data points per second. After the completion of the fifteenth cycle the stimulus remained stationary for five seconds. The beginning of the input blanking phase was cued by a long tone. The stimulus and response markers were visible for the first five cycles of the stimulus pattern. At random intervals during the sixth cycle of the pattern, the *response* marker was eliminated from the screen. The subject continued blind tracking until the tenth cycle. The elimination of the *stimulus* marker was cued by a short tone (duration .5 seconds) during this tenth cycle. Approximately two seconds after the tone the stimulus marker was also eliminated from the screen. A period of seven seconds then elapsed before a double tone signalled the end of the trial. During this period the subject was to produce the same response that he had done prior to the "input blanking". The response made during the middle four seconds of blanking were sampled at a rate of 500 data points per second.

Two sets of data were stored following each block of trials. One set related to the subjects performance on the pursuit tracking task while the second set of data represented the subjects attempts at reproducing from memory a learned sequence of movements.

Data Analysis

Pursuit tracking phase

The error and variance measures that were used in Experiment IV were also used in this experiment. The SD of the movement velocity within each block of trials was used as an index of within-subject variance. The RMSEp (for mathematical derivation, see Figure 20) for each block of trials was used as an index of tracking error. In addition to error and variance measures, a cross-correlation function was calculated between the stimulus and response signals of Trial 7 in each block. The response signal was advanced in time by intervals of 10 milliseconds therefore $\tau=0, .01, .02, .03, .04$ secs.

Input blanking phase

The response record for each subject during this phase was described by a process of harmonic analysis (Beckwith and Buck, 1964). The harmonic components with their relative amplitudes, frequencies and phase relations were obtained by a process of graphical integration using numerical methods. The first step was to set the limits of the cycle and assign the values 0 and 2π, with the general form of the equation being

$$f(\theta) = \frac{A_0}{2} + (A_1 \operatorname{Cos}\theta + A_2 \operatorname{Cos}2\theta \ . \ . \ . \ ) + (B_1 \operatorname{Sin}\theta + B_2 \operatorname{Sin}2\theta \ . \ . \ . \ ) \ . \ . \ . \ \text{(i)}$$

The fundamental cycle was divided into m equal intervals, each of width $\Delta\theta$, where $\Delta\theta$ was equal to the sampling rate of .002 seconds. The harmonic coefficients were then determined by multiplying each of the coordinates by the corresponding numerical values of the desired trigonometric function.

The general form of equation (i) was converted to:

$$f(t) = \frac{A_0}{2} + \sum_{n=1}^{\infty} CnCos(n\omega t - \phi_n) \quad . \; . \; . \; (ii)$$

where

$Cn = \sqrt{An + Bn}$,

$\tan\phi_n = \frac{Bn}{An}$,

$\omega = 2\pi f$ (with frequency in cps), and

$\theta = \omega t$ (with ω in radians/sec).

The first four harmonics of the response signal were analysed. This limitation in analysis was due to the fact that the stimulus was a composite of only three harmonics, $f(t) = \frac{A_0}{2} + CnSin\omega t + \frac{Cn}{2} Sin2\omega\, t + \frac{Cn}{4} Sin\ 4\omega t$. The stimulus signal was sampled through the A/D channel of computer and then these values were analysed using the same programming technique as used for the response. This was done to equate the digital values sampled from the response to that of the stimulus. The actual values for the stimulus waveform were:

$$f(t) = \frac{1456}{2} + 224(Cos\ \omega t) + 112(Cos\ 2\omega t) + 5(Cos\ 3\omega t + 4.7)$$

$+ 56(Cos\ 4\omega t)$, with the period of the fundamental being equal to 2.564 seconds.

The inclusion of the third harmonic is negligible and can be accounted for by instrument error.

Results and Discussion

Pursuit tracking phase

In general, the results from the pursuit tracking phase of the present experiment are similar to the findings of Experiment IV. The graph shown in Figure 27 reflects an improvement in movement consistency for all subjects while the tracking error, shown in Figure 28, declined as the subjects learned the task. Although both movement variability and root mean squared error decreased as a function of trials several aspects of the subjects' performance, as measured by these indicants, are noteworthy. Firstly, there was a wide dispersion of both error and variance scores between subjects early in learning and then as more trials were completed the subjects attained similar levels of proficiency. Earlier studies by Adams (1953), Fleishman (1953), Jones (1962, 1970) and Reynolds (1952) have all found similar results with respect to the individual differences displayed by subjects while learning a motor task. It appears that in both Experiment IV and the present experiment, the subjects attained similar levels of proficiency at the tracking task but the methods by which this level was achieved varied from subject to subject.

A second observation can be made (see variance and error graphs in Figures 27 and 28) relative to tracking error and movement variability during any one block of trials for individual subjects. Subject 1 (R.P.) reduced both error and variance equally up to and including Block 4. However during Block 5 and 6, his tracking error decreased while his movement variance increased. Then during Block 9 there was a further reduction in tracking error with a corresponding rise in variability. The performance of Subject 2(K.M.) during Blocks 4 and 6

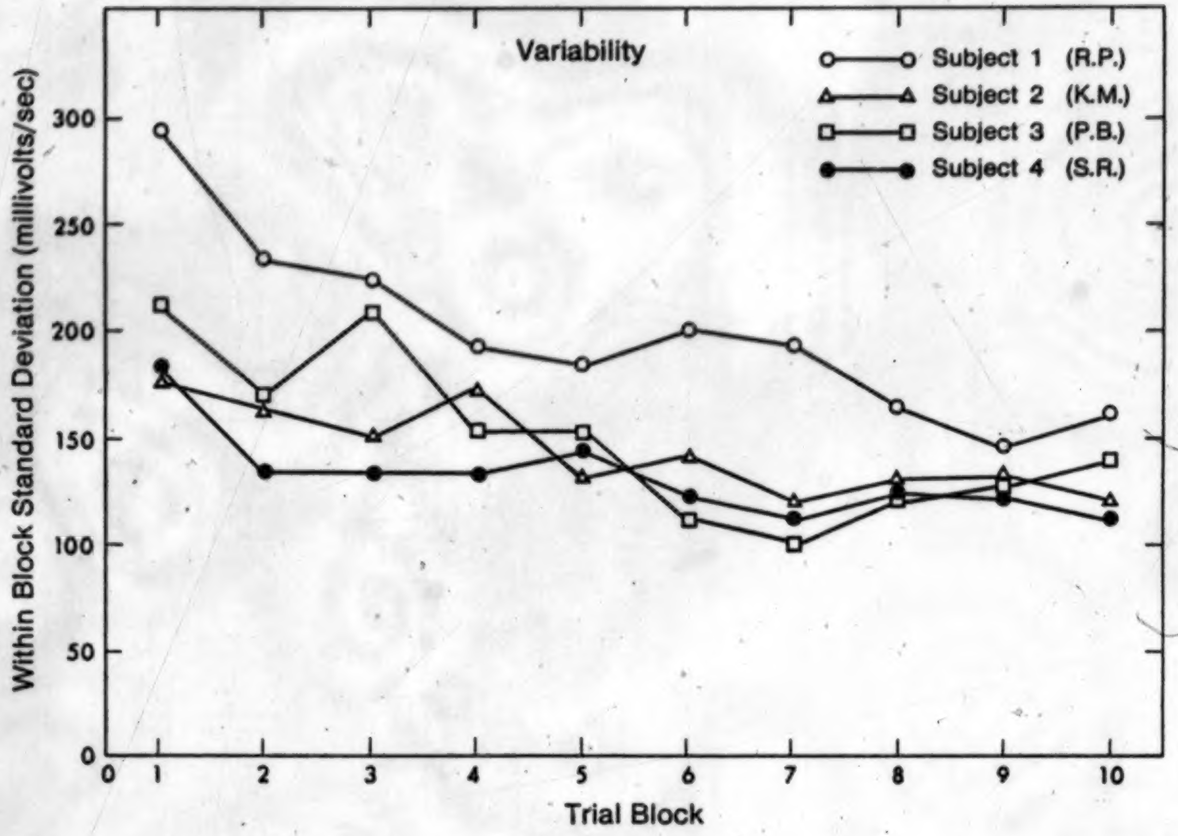

Figure 27. Within subject variance scores for the 10 trial blocks of Experiment V. The standard deviation of the movement velocity was used as the consistency index.

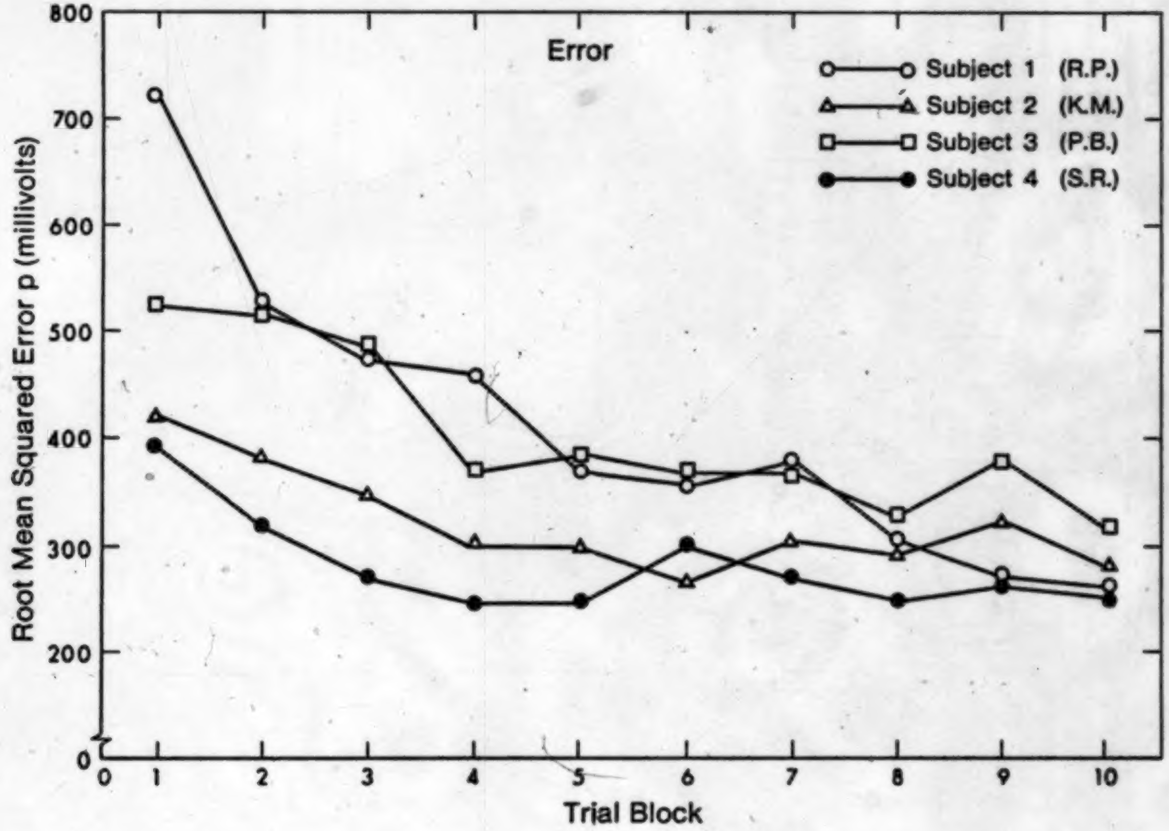

Figure 28. Root mean squared error for the 10 trial blocks of Experiment V. The RMSE p is averaged over the period of the eighth cycle of each trial and summed over the seven trials of each block.

would warrant similar observations. Subject 3(P.B.), on the other hand, ended the experiment with a comparatively high overall error score but acquired a remarkably low overall variance score (c.f. B.G., Experiment IV). These results suggest two possible ways in which error and variance scores, obtained during tracking performance are related. If a subject wishes to reduce his tracking error it may be necessary to change his pattern of responding; hence increase his movement variability. It also follows that if a subject accepts a certain bandwidth of error during several blocks of trials (i.e. tracking error remains relatively unchanged) he may be reducing the variability of his movement pattern, thereby becoming increasingly consistent.

The cross-correlation functions that were used as indices of temporal adjustment of the subjects performance are shown in Table 7. The higher correlation coefficients were notable in the later trial blocks, indicating that the subjects' response was more positively associated with the stimulus later in practice. There is also evidence that the subjects' reduced their overall time lag between stimulus and response. The correlation coefficients approached maximum values earlier ($\tau \to 0$) during Trial Blocks 8 and 10. However, due to the limited number of time intervals used and the relatively small increments in the value of τ, the maximum cross-correlation function was not defined; consequently, the corresponding value of τ was not calculated.

There was a further problem that arose concerning the lead-lag index used and the composite sinusoidal waveform that was chosen as the stimulus. When the response records were examined the subjects consistently made errors at specific places along the stimulus cycle.

Table 7

Crosscorrelation Functions for each Subject

for Blocks 2, 4, 6, 8 and 10, Between Stimulus and Response.

Block	$\tau=0.0$	$\tau=.01$	$\tau=.02$	$\tau=.03$	$\tau=.04$	$\tau=.05$
Subject 1 (R.P.)						
2	.90	.91	.92	.93	.93	.93
4	.91	.91	.91	.92	.92	.93
6	.94	.94	.95	.95	.95	.95
8	.96	.96	.97	.97	.97	.97
10	.96	.96	.97	.97	.97	.97
Subject 2 (K.M.)						
2	.93	.94	.94	.94	.95	.95
4	.96	.96	.96	.96	.97	.97
6	.96	.97	.97	.97	.98	.98
8	.95	.96	.97	.97	.98	.98
10	.96	.97	.97	.97	.98	.98
Subject 3 (P.B.)						
2	.91	.91	.92	.93	.93	.94
4	.94	.94	.95	.95	.95	.96
6	.94	.94	.95	.95	.96	.96
8	.96	.96	.96	.96	.96	.97
10	.94	.95	.95	.96	.97	.97
Subject 4 (S.R.)						
2	.94	.95	.96	.96	.96	.96
4	.96	.96	.97	.97	.98	.98
6	.96	.96	.97	.97	.98	.98
8	.96	.97	.97	.97	.98	.98
10	.97	.97	.98	.98	.98	.98

Note. Values of τ measured in seconds.

The major proportion of error was located at the positions along the waveform that changed speed but not direction. This was also the case in Experiment IV (see Figure 23). During these two phases of the cycle the stimulus slowed down for a brief period of time. The subjects' response, however, did not reflect the change in speed and at this point the subjects moved in advance of the stimulus. The overall lag index used did not differentiate between those specific areas along the track where the subject may have led or lagged behind the stimulus. Poulton (1974) has also questioned the relevance of using an overall time error measure that does not give a complete picture of the results. Two contentious issues were raised by Poulton. First, the overall cross-correlation function did not differentiate between the large lag time at track reversals and the comparatively smaller lag time at points of inflection. Second, the remnant of the response was not accounted for when overall average time lags were reported. These criticisms along with the problems encountered when a composite sinusoidal waveform was used as stimulus pose a question as to the suitability of the cross-correlation function as an index of temporal adjustment of performance. A possible modification to this index of performance was suggested by Poulton. The crosscorrelation function for a number of band frequencies that go into making up both the stimulus and response can be calculated. Since the problems encountered in this experiment were directly related to the composition of the stimulus, the suggested modification to the crosscorrelation function would seem to be suitable when using composite sine waves as stimulus.

Input blanking phase

The subjects' responses that were made in the absence of visual

Table 8

Mean and Variance Values of the Harmonic Coefficients (A_0, Cn) Phase Relationships ($t\phi_n$) and Period (p) for Blocks 3, 5, 7 and 9 Averaged Across Subjects

		Block				Stimulus
		3	5	7	9	
p	σ	51.41	34.78	28.23	30.31	
	$\bar{x}$	2596	2584	2620	2642	2564
A_0	σ	26.25	16.75	17.50	15.50	
	$\bar{x}$	1392.25	1382.00	1407.50	1418.50	1456
C_1	σ	11.75	14.75	7.00	9.00	
	$\bar{x}$	242.25	230.25	227.00	224.50	224
C_2	σ	13.00	6.75	5.75	5.75	
	$\bar{x}$	105.00	109.25	112.00	116.25	112
C_3	σ	4.25	4.50	4.50	4.75	
	$\bar{x}$	18.50	16.25	16.00	23.25	5[a]
C_4	σ	3.00	2.25	2.00	1.95	
	$\bar{x}$	13.75	16.25	18.25	20.00	56
$t\phi_1$	σ	0.21	0.18	0.16	0.10	
	$\bar{x}$	0.14	0.06	0.10	0.19	0
$t\phi_2$	σ	7.39	0.83	0.65	1.05	
	$\bar{x}$	-1.87	0.52	0.65	0.50	0
$t\phi_3$	σ	3.77	4.28	1.98	0.45	
	$\bar{x}$	-1.70	-0.25	-0.17	-0.40	4.7
$t\phi_4$	σ	3.35	2.23	2.68	1.25	
	$\bar{x}$	-1.25	0.48	-0.04	0.07	0

Note. p is measured in milliseconds; A_0, Cn is measured in millivolts. $t\phi_n$ is the tangent of the phase angle.

[a] Round out to zero.

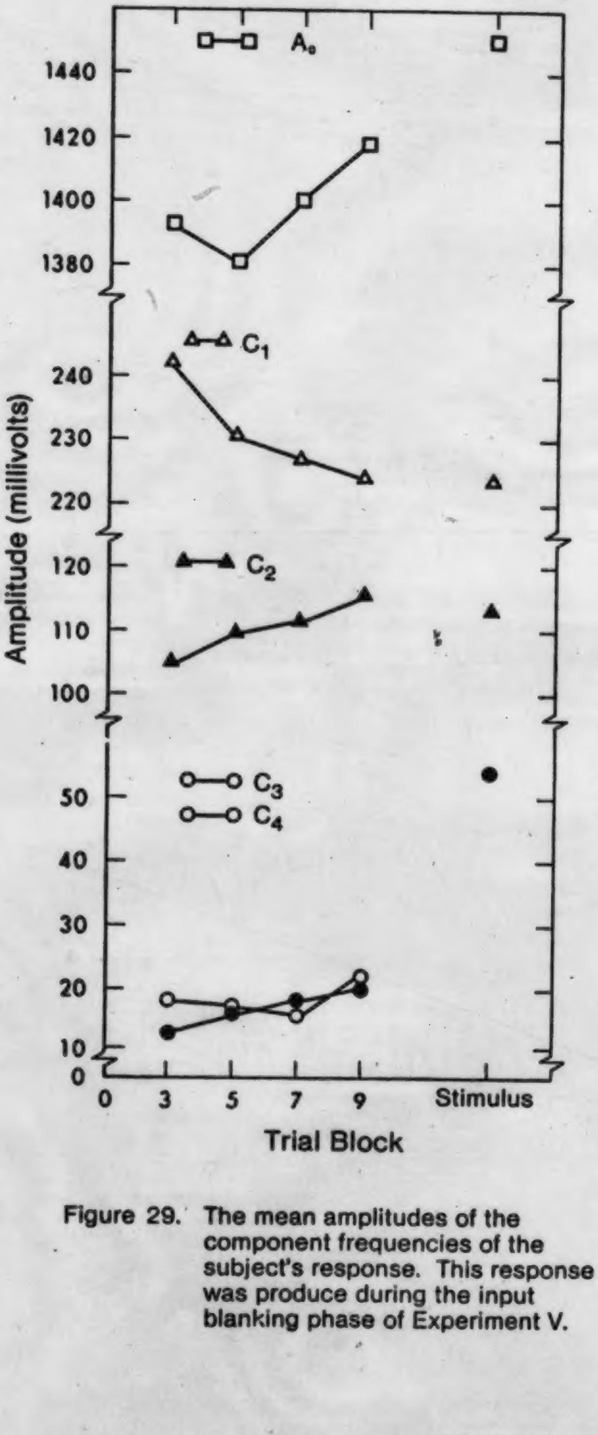

Figure 29. The mean amplitudes of the component frequencies of the subject's response. This response was produce during the input blanking phase of Experiment V.

indicators (input blanked) were subjected to a Fourier analysis. These responses can be considered as complex signals and may be expressed as a combination of simple harmonic components each having its own amplitude, frequency and phase relations with other components. Specifically, each subject's response was decomposed into a major fundamental and three harmonics. It was possible therefore to gain the following information about the response:

(1) A_0: A harmonic coefficient that relates to the axis of symmetry about which the response is produced.

(2) Cn: Harmonic coefficients that relates to the amplitude of each harmonic.

(3) $t\phi_n$: The tangent of the phase angle relations between harmonics.

(4) p: The period of the fundamental harmonic (C_1)

During each block of seven trials an individual subject would complete seven trials with the input blanked. Each of these seven responses for individual subjects was analysed and a mean and within-block variance figure was calculated for each component. The mean and variance figures were then averaged across subjects, and the results tabulated (see Table 8). The harmonic coefficients from which the amplitudes were determined can be seen in Figure 29.

On the right hand side of Figure 29 are the component values of the stimulus signal. It appears that as the subjects learned the task, the response that they produced from memory approached the criterion waveform. This seemed to be the case for the coefficients A_0, C_1 and C_2, however, the coefficients of the third and fourth harmonics remained relatively undefined with respect to the criterion. In addition to the finding that certain components of the response became more like those of the stimulus, the stability of those components (A_0, C_1 and C_2) also improved as a function of trials. The standard deviation figures in Table 8 represent the stability with which the subjects produced each component of the response within each block of trials. The SD for A_0, C_1 and C_2 decreased as learning progressed, while no appreciable changes in the variability of producing the higher harmonics occurred.

The tangents of the phase angles can be seen in the lower half of Table 8. The mean value of $t\phi_1$, which represents the degree to which the fundamental was in phase with the remaining harmonics, is for all intents and purposes, zero. This indicates the absence of a phase lag or lead with respect to the complete waveform. Whereas the phase relationship of the fundamental was always relatively accurate with respect to the criterion, the tangent of the phase angle ($t\phi_2$) for the second harmonic only approached zero after several blocks of trials.

Also shown in Table 8 are the mean and SD figures for the period of the fundamental. The period of the response became more stable (see SD values) within each block of trials the mean value increased and exceeded the period of the stimulus signal. Several authors (Magdaleno et al., 1970; Pew, 1974a; Vossius, 1965) have found similar results when they have used the input blanking methodology to investigate the subjects generated pattern of movements. The subjects appeared to produce their responses within a framework of time that was in excess of the period of the stimulus; even though the principle events that occurred within the response had an equivalent proportional time base to that of the stimulus. The relational temporal properties of the response therefore, appeared to be acquired before the response was placed into any absolute time frame.

The learned response that was produced by subjects from memory during input blanking appears to have been organized in terms of component frequencies of that response. Early in learning the subjects try to produce a complete response that they believe is a true representation of the stimulus signal. At this stage in acquisition the subjects are concerned with only the lower harmonics (A_0, C_1 and C_2 in this case), the axis of symmetry being adjusted along with the fundamental and second harmonics. The amplitudes and phase relationships of these lower harmonics appear to be of major concern to the subjects early on in practice while the higher harmonics remain relatively unimportant to the description of the response. A natural development of this thesis would be that the higher harmonics only become relevant after increased amounts of practice at the task. Experiment VI was designed to explore this possibility.

EXPERIMENT VI

Experiment VI was an extension of Experiment V. One subject (S.R.) from the previous experiment was asked to return and undergo more intensive training at the task she had learned during Experiment V. There were two reasons for acquiring additional data from the extended practice trials.

First, during the pursuit tracking phase of both Experiment IV and V, the subject's performance as measured by RMSEp and SD of movement velocity appeared to reach a plateau. The within-subject variance and root mean squared error scores plateaued at approximately 110 millivolts/second and 250 millivolts respectively. This plateau of performance could be either reflective of the stage of learning at which the subjects were operating, or be a basement effect caused by the inability of the tracking equipment to register any improvement in performance beyond the attained level. For each block of trials the RMSEp minimum and maximum values were 105 and 1500 millvolts respectively. Also the response sampling error was only .3%, hence the minimum response variance score possible was well below those values recorded during the later trial blocks of Experiment IV and V. Therefore it was expected that S.R.'s tracking performance after an extended training period should improve both with respect to the error and variance measures used.

Second, the thesis expressed in the discussion of the preceding experiment was that the accuracy and consistency with which subjects produced, from memory, a specific movement pattern improved as a function of trials. The pattern of movements that subjects generated while the input was blanked was expected to approximate that of the stimulus. The findings from Experiment V, however, were only partly supportive of this thesis. That is, while the fundamental and the second harmonic of the response approached that of the stimulus, the higher harmonics remained relatively unstable and illdefined. Earlier studies that have investigated motor learning and movement consistency used an extensive number of acquisition trials in an applied and industrial setting. Changes in performance were recorded after several thousand trials at the task, be it cigar rolling (Crossman, 1959), sheet metal cutting (Lindahl, 1945) or transmission of morse code signals (Bryan and Harter, 1899). In the present experiment extended periods of practice were used in order to monitor the further development of the subject's response that was produced during input blanking. It was hypothesized that the harmonic components that make up the response will become more like that of the stimulus.[†] Specifically, the amplitude determining coefficient (C_3) of the third harmonic should decrease and and approach zero while the amplitude of the fourth harmonic should increase and approach a value that is equivalent to one half of the amplitude of the second harmonic.

[†] $f(t) = \frac{A_0}{2} + C_1 \left(\text{Sin}\omega t + \frac{1}{2}\text{Sin}2\omega t + \frac{1}{4}\text{Sin}4\omega t\right)$.

Method

One of the four subjects who completed Experiment V (S.R.) volunteered to continue learning the tracking task for an extended period of time. A break of two days occurred between the completion of Experiment V and the beginning of Experiment VI. Three[†] experimental sessions were completed during this experiment (E1, E2, and E3). Each session was comprised of four training periods followed by a testing period. During one training period the subject tracked the stimulus signal (as used in Experiment V) for approximately two minutes (50 cycles). Between each of the four training periods S.R. rested for a subject controlled time period which did not exceed two minutes. After completing all four training periods (200 cycles) S.R. was given a 10 minute rest before beginning the testing period. This testing period was identical to that used in Experiment V, in that it consisted of seven trials of pursuit tracking and input blanking. Also the data analysis used in Experiment V was used during the pursuit tracking and input blanking phases of the testing period in the present experiment. The RMSEp was used as an indicant of errorful performance while the SD of movement velocity was used to describe the consistency of responses made within a block of trials. The responses that S.R. produced while the input was blanked were decomposed into simple harmonic components by means of a Fourier analysis.

[†] The subject returned for a fourth experimental session, but due to equipment problems only results from three sessions are reported here.

Results and Discussion

Pursuit Tracking Phase

Throughout Experimental sessions E1, E2 and E3, S.R.'s performance on the tracking task, as measured by RMSEp and within-subject variance, improved. The tabulated results of Table 9 reflect this improvement in performance. After the first extended training session (E1) S.R. reduced her tracking error and produced a more consistent movement pattern. The bandwidth of error accepted by S.R. and the variability of movement that she displayed during E1 remained relatively stable after session E2. That is, there was very little change in either of the assigned measures. However, at the end of the third period of extended practice[†] the subject drastically reduced her RMSEp, while increasing her movement variability. This extra reduction in tracking error appeared to have necessitated certain changes in the movement pattern used to respond to the stimulus. The changes in the movement pattern had the effect of reducing tracking error but increasing variability.

Input Blanking Phase

The coefficients of the component frequencies that go into making up the response produced during the input blanking phase can be seen in Table 10.[††] Both C_1 and C_2 and their respective phase relationships $t\phi_1$ and $t\phi_2$ appeared to be relatively stable and accurate with respect to the stimulus. This result was to be expected since the results of

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[†] At this stage in training S.R. had tracked a total of 1965 cycles of the stimulus signal (incl. Expt. V).

[††] When comparing these results with those of Table 8 (Expt. V), it must be kept in mind that the results of Table 8 are averaged across subjects while those of Table 10 are for an individual subject (S.R.).

Table 9

The Within-Subject Variance and RMSEp

Scores of S.R. for Experiment V and VI

Block	1	2	3	4	5	6	7	8	9	10	E1[a]	E2[a]	E3[a]
SD of Movement Velocity	179	132	139	135	151	121	114	131	131	117	88	84	119
RMSEp	397	307	271	250	249	307	277	249	267	257	237	232	205

Note. Recorded values are measured in millivolts/sec (SD of movement velocity) and millivolts (RMSEp).

[a] Extended practice sessions completed during Experiment VI.

Table 10

Mean and Variance Values of the Harmonic Coefficients (A_0, Cn), Phase Relationships ($t\phi_n$) and Period (p) for Blocks E1, E2 and E3 Produced by S.R. during Experiment VI.

		Block			Stimulus
		E1	E2	E3	
p	σ	25.16	30.62	21.80	
	$\bar{x}$	2654	2616	2582	2564
A_0	σ	9.25	9.25	10.50	
	$\bar{x}$	1392	1386	1414	1456
C_1	σ	10.21	10.48	6.13	
	$\bar{x}$	248	231	222	224
C_2	σ	7.25	6.84	4.12	
	$\bar{x}$	115	116	112	112
C_3	σ	5.71	4.84	6.62	
	$\bar{x}$	17	11	9	5[a]
C_4	σ	4.26	3.12	2.41	
	$\bar{x}$	18	24	25	56
$t\phi_1$	σ	0.15	0.15	0.13	
	$\bar{x}$	0.13	0.00	0.00	0
$t\phi_2$	σ	0.61	0.52	0.13	
	$\bar{x}$	0.73	0.62	0.33	0
$t\phi_3$	σ	0.71	3.98	5.16	
	$\bar{x}$	0.08	-0.51	1.62	4.7
$t\phi_4$	σ	6.12	5.04	2.04	
	$\bar{x}$	-2.14	-0.81	0.37	0

[a] Round out to zero.

Experiment V show the fundamental and second harmonics to be relatively well defined and invariant during Trial Blocks 9 and 10. Of interest to the present study were the changes that occurred to C_3 and C_4. After three sessions of extended practice the response that S.R. produced from memory no longer contained a third harmonic of any significant amplitude. On the other hand, the amplitude of the fourth harmonic of the response appeared to increase in size as a function of training. The responses that were made during the input blanking phases of Blocks 4, 10 (Expt. V) and E3 (Expt. VI) are shown in Figure 30. The inclusion of the added detail pertaining to changes in track speed can be seen. The second reversal of the response waveform always appears to undershoot the criterion waveform. The period of the fundamental also undergoes two distinct changes. During Experiment V, subjects increased the time taken to complete a cycle. However, S.R.'s mean periodic time for the cycle began approximating the stimulus. It appeared that one of the features of the response that the subject adjusts at this later stage of learning is the absolute temporal qualities of the criterion. The additional adjustments that were recorded during the present experiment were mentioned during conversation with S.R. after Trial Block E3. S.R. reported that she was now more accurate during the input blanking phase and she was aware of improvements in response. These improvements were related to changes in the speed of the waveform.

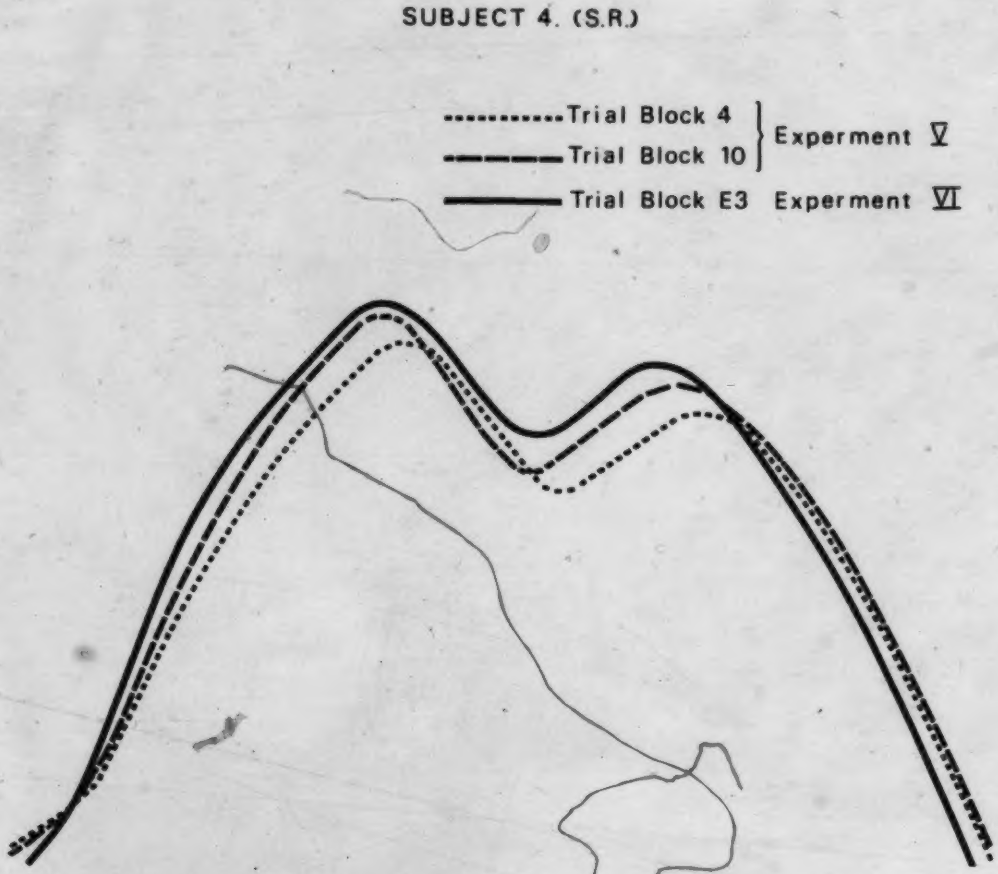

Figure 30 Responses produced by S.R. during the input blanking phases of Experiment V (Blocks 4 and 10) and Experiment VI (Block E3)

EXPERIMENT VII

The stimulus signal used in Experiment IV, V and VI was a composite of three sine waves, with a frequency ratio of 4:2:1. The signal therefore repeated itself every four cycles of the top track frequency and the period for one repetition was 2.56 seconds. The periodicity of the signal made the track highly predictable. That is, after a limited number of trials the subjects had a general idea of the course the stimulus would take. Also, the frequency of the waveform enabled the subjects to detect a rhythm of movement. Magdaleno et al. (1970) hypothesized that when subjects track stimulus signals at frequencies between .75 and 1.0 Hz they activate a pattern generator and that this activation is related to the subjects' detection of rhythm within their response. In order for subjects to reduce error while tracking a periodic and predictable waveform they first generate a movement pattern that they believe to be the best estimate of the stimulus. The degree of correspondance between the subject generated pattern and the stimulus signal is therefore directly related to the number of error corrections made. The generation of a repeating pattern from some form of memorial representation is therefore basic to the development of any discussion relating to the organization and learning of a movement sequence.

Adams (1961) and Poulton (1952) have shown that subjects can improve their performance by using predictable aspects of the input. On the other hand, subjects find difficulty in improving their tracking performance when the input is unpredictable. Unpredictability can be assured when the frequency and phasing of the waveform are varied randomly, or the waveform is a composite of three or more sine waves with proportional frequencies that preclude any repetition of the waveform within approximately 10 to 15 seconds. The improvements recorded in tracking performance during Experiments IV, V and VI were attributed largely to the predictable and rhythmic qualities of the stimulus. Experiment VII was designed to record the changes that occur in produced tracking error when subjects track an unpredictable waveform. Since the major portion of error reduction took place during the first six trial blocks in the previous experiments, only six testing sessions were used in the present study.

Method

Subjects

Three male and two female subjects, ranging in age from 20 years to 23 years, volunteered to take part in this experiment. All five subjects, who were undergraduate students at the University of Alberta, wrote with their right hand. The subjects had never taken part in any previous tracking experiment.

Apparatus and Task

The apparatus and task were identical to that used in Experiment IV, with one exception. The stimulus signal was made unpredictable. This was achieved by varying the phase angles between harmonics and also varying the frequency of the harmonics of the signal. The frequencies were chosen from a normal distribution of frequencies that had their mean value equivalent to that of the component frequencies used in Experiment IV (i.e. $f(t) = \frac{A_0}{2} + C_1(\mathrm{Sin}\,\omega t + \frac{1}{2}\mathrm{Sin}\,2\omega t + \frac{1}{4}\mathrm{Sin}\,4\omega t)$).

The subjects completed one experimental session per day for six consecutive days. Each session began with a training phase in which the subject tracked a sine wave whose frequency was equivalent to the mean frequency of the fundamental used in Experiment IV. The subjects then completed the testing phase of the experiment. This phase consisted of seven trials in which the subjects tracked an unpredictable waveform for 39 seconds during one trial. The response to the middle 2.6 seconds of each trial was sampled at a rate of 1000 data points per second. These data were then used to calculate the RMSEp for each block of trials.

Results and Discussion

The results from Experiment VII were tabulated (see Table 11). Whereas the mean RMSEp scores of the five subjects decreased only marginally, the individual records of each subject appear to be slightly more informative. For example, Subject 2 (M.H.) continued to improve her performance up to and including the sixth block of trials. Also, Subject 4 (D.B.) reduced his tracking error (with the exception of Block 4) throughout the experiment. The remaining three subjects appeared to show very little, if any, improvement in tracking performance as measured by RMSEp.

When the subjects were questioned as to the coherency inherent in the stimulus course they all considered the stimulus course to be completely unpredictable. That is, the subjects detected no repeating pattern in the stimulus. The error that all subjects felt to be most harmful to their performance was that of direction. The first priority of all subjects was to be going in the same direction as the stimulus, and in an effort to achieve this, they all attempted to follow the stimulus as closely as possible. None of the subjects reported any attempts to anticipate the movement of the stimulus. Other data that was acquired from experiments by Noble and Trumbo (1967) and Noble, Trumbo, Ulrich and Cross (1966), also indicated that the primary goal for a subject to achieve while tracking early in practice was to acquire the correct direction of the stimulus.

The substantial improvements in tracking performance that were evident from the results of Experiments IV and V were not found during this present experiment. The slight reduction in tracking error that was recorded could have been due to the subjects learning the control

Table 11

RMSEp Scores for the Five Subjects made

during each of the Six Trial Blocks of Experiment VII

		BLOCK					
Subject		1	2	3	4	5	6
1.	(S.C.)	449	440	411	374	434	490
2.	(M.H.)	478	455	475	459	432	410
3.	(M.Y.)	523	465	497	471	511	505
4.	(D.B.)	495	431	414	507	392	430
5.	(D.G.)	483	492	516	474	500	502
	$\bar{X}$	485	456	462	457	454	467
	σ	24.04	21.24	42.92	44.44	44.92	39.53

Note. RMSEp was measured in millivolts.

functions of the task.[†] Also the between-subject variance of the error scores did not decrease throughout the experiment. In summary, therefore, it appears that the periodicity and predictability of the waveform used during Experiments IV, V and VI was largely responsible for the improvements in tracking performance that were found. When the stimulus signal is made aperiodic and relatively unpredictable only slight improvements in tracking performance as measured by error scores are recorded.

[†] For a detailed review of control function learning, see Kelley (1968).

GENERAL DISCUSSION

The primary reason for undertaking this series of experiments was to investigate the relationship between selected measures of skilled performance and their value as both descriptors and predictors of the processes that underlie the organization and learning of a complex movement sequence. Several limitations were adopted to give structure and direction to this group of experiments. The perceptual motor task chosen was a pursuit tracking task in which the relationship between the stimulus and response display was varied. Four derived measures of performance were used to make inferences about the behaviour of the subject during the tracking task. These indicants included error scores (RMS error), frequency analysis (Fourier transform), lead-lag index (crosscorrelation function) and a consistency index (within-subject variance).

Concern over the analytic description of a subject's response during skill acquisition was manifest from two initial sources. Firstly, two classic experiments by Thorndike (1931) and Seashore and Bavelas (1941) emphasized the problem of construct validity. Thorndike found that mere repetition of a hand movement to the instruction "move four inches" did not result in improvement unless practice was corrected by K.R. This finding was challenged by Seashore and Bavelas, who re-examined some of Thorndike's data and found indications that successive responses became more consistent, although there was no general trend toward the prescribed target length. Annett (1969) has since suggested that intertrial consistency can be taken as an index of learning along with simple error scores.

A second insight into the problem of assigned measurement was gained from a more recent source. Pew and Rupp (1971) proposed two quantitative measures of skill development. These measures, subject's responsiveness (system gain) and time delay, taken together were considered to be more representative than simple error scores. The authors conclude their article by stating:

> It is easy to show changes in error scores, but it takes an ingenious E (experimenter) to design a tracking experiment in which changes in error scores alone provide a degree of analytic insight into the nature of the skilled performance that goes beyond the statement that manipulation of a particular independent variable produced a change in performance. (p. 6)

Results from the present series of experiments support the view that one dependent measure of performance cannot adequately describe those changes that occur in a subject's response over extended practice. Each measure used adds to the description of the performance and provides a more integrated view of the manner in which a subject acquires a movement sequence. Error scores alone may indicate a general level of proficiency at the task, but derivations of variance and time delay indices give both additional qualitative and quantitative assessments of performance at this level.

Temporal Adjustment of Performance

The overall time delay of a subject's response, when derived from the crosscorrelation function, has two constituent elements. The first is an intrinsic processing delay accounted for by central processing and the neuromuscular system, while the second appears to be due to a subject's ability to predict trends inherent within the input signal. Consequently, the decrease in the time lag of the subject's response found in Experiment I could be explained solely in terms of improvements with respect to central processing delays, as 80% of the stimulus signal was derived from randomly selecting one of three transition points.

However, due to the fact that there were only three transition points, exact stimulus course prediction was possible up to 60% of the time. At the left and right transition points the subsequent direction of the stimulus was fully predictable, therefore the subject's performance was probably influenced to a large extent by prediction. The stimulus signals used in Experiment II, III and V were periodic and the subjects required only a limited number of trials before they were able to accurately report the general features of the course. This knowledge of the stimulus course made prediction possible and all subjects reduced their overall time lag during these experiments.

The corrective actions displayed by subjects during Experiments I and II appeared after approximately four trial blocks. These corrective actions, that probably result from anticipatory tracking behaviour, should produce an increase in the variability of movement velocity; that is assuming the correction is not repeated on each trial at the same point in time. The change in strategy from following the track to anticipating its course was reflected by a concurrent change in the consistency index used. An increase in within-subject variance was evident at approximately Trial Block 4 during each of these experiments. In summary, therefore, it appears that a subject will adopt a following strategy that gives way to a form of anticipatory behaviour once the subject can predict future states of the stimulus. Also the onset of any anticipatory tracking behaviour may be represented as an increase in within-subject variance.

The use of the lead-lag index as an indication of overall time error during the acquisition of a tracking task has a number of severe limitations. Some of these are related to signal complexity and were outlined earlier in the discussion following Experiment V. Other disadvantages and restrictions to its use were put forward by Poulton (1974). In view of the problems associated with an overall time delay index, a more comprehensive measure such as a lead-lag index derived from the component frequencies of both the stimulus and response waveforms might be more appropriate.

Crosscorrelation and autocorrelation techniques can be related to a Fourier analysis as all three are mathematically compatible. The autocorrelation function has the same inherent information within it as does the power spectrum of a waveform. The autocorrelation is presented in the form of a function of time rather than frequency. Anstey (1964) outlines the relationship in a review of correlation techniques.

> Thus a *waveform* is synthesised by combining: Fourier components with amplitudes given by the amplitude spectrum and the phases given by the phase spectrum; the *autocorrelation function of the waveform* is synthesised by combining Fourier components with the amplitudes given by the power spectrum of the waveform, and with zero phase. (p. 358)

Since many of the recent investigations completed in the area of Motor Learning deal with the temporal aspects of performance, the use of autocorrelation and crosscorrelation techniques should become increasingly important. However only a handful of studies that have examined the temporal qualities of organized responses have employed correlation techniques, these being Shaffer (1978) and Wing and Kristofferson (1973).

Consistency of Performance

The application of the performance consistency measure used in this set of experiments was based upon two tenants. First, that the within-subject variance can be partitioned out from total variance found in the subject's response. Fiske and Rice (1955) and later Franklin Henry (1959) termed this subject related variance, intra-individual variation.[†] More recently Schmidt and his co-workers (1979) have used this concept in studying the variance produced by a subject during the execution of a rapid aiming movement.

Secondly, the within-subject variance was computed using movement velocity data. This was done because evidence from several sources (Fuch, 1962; Pew, 1974a; Poulton, 1974) suggests that a subject does not execute error corrections on the basis of position errors alone. Rather he takes into account the trends and rates of change of the error signal when forming decisions about the size of the corrective responses required. Further, the stimulus signal composition and the subject's present level of learning are directly related to the derivative of the error signal to be used. That is, as the subject learns the tracking task, he tends to operate upon higher derivatives of the resulting error signal (Fuchs, 1962).

The results from Experiments I and II were supportive of the conclusions drawn from earlier studies (Glencross, 1973; Higgins and Spaeth, 1972; Lewis, 1953; Tyldesley and Whiting, 1975) that skilled performance is normally characterized by a highly consistent and reproducible pattern of movements. A more detailed picture of the increase in movement consistency was examined in the third experiment. Apparently the accelerative and decelerative portions of a movement within a sequence accounts for the major portion of the within-subject variance score. The mid portion of the movement (maximum velocity) on the other hand tends to stabilize as a function of trials and only contribute fractionally to the within-subject variance.

[†] See Appendix B for a brief review.

Two explanations accounting for the decrease in movement variance are possible. These explanations focus attention toward different levels of analysis. At a physiological level of analysis, Glencross (1973), Lundervold (1958) and Person (1958) considered the improvement in movement consistency that occurred in the later stages of skill acquisition to be an outcome of the temporal restructuring of the response units as measured by electromyographic analysis.

> With training, the agonist muscles' activity appeared as a regularly occurring short burst of activity in the movement cycle . . . Thus the more precise phasing of the muscle activity is accompanied by an increase in consistency of the torque record and hence the movement pattern as a whole. (Glencross, 1979, p. 161)

A behavioural analysis explanation, wherein action is defined as the environmental consequence of the movement, has been offered as a second possibility. Although the two levels of analysis are different there appears to be a logical overlap in the explanation of the phenomenon. For example, the decrease in intra-individual variability during Norrie's (1967) experiment was accounted for by a process of movement reorganization. The curves for intra-individual variance commenced with an initial rapid drop followed by a slower downward trend for complex movements, but a relatively small decline with practice for the simple movement. It was therefore suggested that movement reorganization in learning a simple movement was small and occurred early in practice, while that for a more complex movement was larger and required more practice to reach the same limits of simplification. The explanation offered by Higgins and Spaeth (1972) was in some ways consistent with Norrie's viewpoint. They proposed that as learning progressed, the subject revised his motor plan to achieve a consistent, smooth displacement curve.

Both Neisser (1976) and Glencross (1979) utilized this concept of adaptation of performance when defining a skillful performer. The results from the present series of experiments provide some insight into the way in which a movement sequence is adapted to meet the environmental demands of the task. The errors made on the tracking task are related to the adjustments made to the sequence of movements that are generated by the subject. During each trial the subject appears to produce a pattern of movements that he believes is a close approximation of the stimulus. Both elementary and higher level control systems operate upon this generated pattern to correct the selection error that was made. Errors in this sense are caused by an incorrect selection of movement patterns. The parameters upon which selection is made can be measured in terms of amplitude, frequency and phasing of the movement. Early in learning, adaptation and updating occur frequently, hence the variance of the movement pattern within each block of trials is large. However, as the generated pattern becomes a closer approximation to the stimulus less adaptation is necessary. The subject uses the perceived error to determine whether or not an update is required. Additional evidence for this statement comes from the results of the final extended block of trials completed during Experiment VI. As was noted earlier, results from Trial Block E4 were not reported due to equipment problems. The top of the response marker was slightly superimposed upon the bottom of the stimulus marker[†] during this final block of trials. Not until after the experimental session was this brought to the attention of the experimenter. The results showed a decrease in error score but a large increase in the variability of movement velocity. The subject (S.R.) also noted that the error was more "noticeable" due to the response making high frequency oscillations about the stimulus. The closer the response marker was to the stimulus the more perceivable the error became. The subject responded to this change in stimulus and response display by making frequent adaptations to the generated movement pattern. The stability and accuracy of the generated movement pattern may therefore be considered paramount to skillful performance.

[†] During all other trials in Experiment IV, V, VI and VII the response marker was 5mm below the stimulus.

The Organization of Movements Produced from Memory

Experiments V and VI were designed to examine the development of the pattern of movements that were produced from memory during the input blanking phase of a tracking task. The responses produced from this memorized control sequence stabilizes and approximates the stimulus only after an extended number of practice trials. As well, subjects appear to organize their response in terms of the component frequencies that make up the response. There are several lines of evidence supporting the suggestion that the complexity of the movement is related to the frequency content of the waveform. For example, Pew (1974a) writes

> The frequency content of these complex but highly overlearned waveforms will dictate the mode of control after the level of predictability has been achieved. (p. 9)

Also, Magdaleno, Jex and Johnson (1970) proposed an input predictability scheme that was intended to serve as a guide to structuring and interpreting experiments for manual control-displays. Their scheme required that the input signal be varied along two dimensions. These were: (a) waveform time variations that had the effect of decreasing the course coherency and; (b) waveform feature variations (increasing the number of component frequencies) that had the effect of increasing the waveform shape complexity.

At a behavioural level of analysis the thesis put forward in this discussion is based upon a process oriented description of response organization as proposed by Glencross (1978). It includes the assumption that an elemental response unit at this level is equivalent to a simple harmonic component of the complex movement sequence. Glencross outlines seven sub-processes involved in response organization:

> 1. *Representation and Discrimination of Response Units:* the discrimination and selection of appropriate response units.
> 2. *Sequencing:* the organization of the selected units into an effective sequence or order.
> 3. *Phasing:* the temporal structuring of the units in the sequence.
> 4. *Gradation:* the grading of the units and the response as a whole in terms of physical effort.
> 5. *Timing:* the timing of the whole response to an external event or object.
> 6. *Response Selection:* the selection of alternate possible responses.
> 7. *Motor Control:* Cognitive structure controlling the actual actions.
>
> (Glencross, 1979, p. 159)

The results from Experiment V and VI suggest that when a subject produces a learned movement sequence his concern early in learning is to define and stabilize the amplitude of the major fundamental of the response waveform. This stage appears equivalent to the representation and discrimination of response units proposed by Glencross. Considerable supportive evidence comes from tracking studies. Elkind (1956) speculated that the subject attempts to generate a sinusoidal response and then modulate it to reproduce the envelope of the input. Along similar lines of inquiry Magdaleno et al. (1970) postulated a "Successive Peaks Hypothesis" for tracking varying waveforms.

> In tracking a narrowband input, the pilot soon recognizes the basic sine wave character of the signal, generates a sine wave output, and attempts to aim it at the next peak, based on his observations of successive earlier peaks. (p. 407)

At the same time as the first and second harmonics of the response are being selected, the phase relationships among these harmonics are being restructured and stabilized. The phasing of the amplitudes concerned appears to be an integral part of the organizational process. The fact that this process of phasing is occurring in parallel with the selection process may be additional evidence in support of the work of Summers (1975, 1977), who contends that the event structure and timing (phasing) structure of a skill are not completely independent representations. Therefore, relative timing between submovements in a movement sequence may be stored as part of the program defining the sequencing component.

Restructuring of response units not only refers to the sequencing and phasing of already selected units, but also to the establishment of higher harmonics that are present within the response sequence. For example, the fourth harmonic was only established as a response element during the final extended trial blocks of Experiment VI. This occurred after the phase relationship between the fundamental harmonic and the second harmonic had been stabilized. It would appear therefore that the development of an accurate movement response requires a large number of extended periods of practice, during which time movement detail is added to the generated pattern. In the present experiments this detail was represented as higher harmonics of the complex response.

A further development in the formation of an accurate movement pattern was concerned with the overall timing of the movement sequence (period of the waveform). Glencross made the distinction between "timing" and "phasing". Whereas timing was related to the adjustment of the whole response with respect to the environment, phasing was concerned with the temporal structuring of the units in the movement sequence. Therefore timing can be looked upon as being an absolute property while phasing is relative. The period of the waveform that subjects produced during Experiment V was greater than that of the stimulus. At the same time the relational phasing of events (harmonics) within the response sequence was proportional to the relational phasing of events within the criterion waveform. Observations of the response records from the input blanking study of Vossius (1965) would lead to similar conclusions.

The thesis outlined here has not been exhaustive with respect to the many subprocesses involved in the organization of movement sequences, nor has it outlined any rigorous transfer function that describes the human operator involved in a tracking task. The intent was to propose a method of analysis, that would more fully describe some of the organizational subprocesses that occur when a subject learns a movement sequence.

References

Adams, J. A. The prediction of performance at advanced stages of training on a complex psychomotor task. *USAF Human Resources Center Research Bulletin*, 1953, No. 53-49.

Adams, J. A. Human tracking behavior. *Psychological Bulletin*, 1961, *58*, 55-79.

Annett, J. *Feedback and human behavior*. Harmondswork: Penguin, 1969.

Anstey, N. A. Correlation techniques - A review. *Geophysical Prospecting*, 1964, *12*, 355-377.

Bahrick, H. P., Fitts, P. M., & Briggs, G. E. Learning curves -- facts or artifacts? *Psychological Bulletin*, 1957, *54*, 256-268.

Bahrick, H. P., & Noble, M. E. Motor Behavior. In J. D. Sidowski (Ed.), *Experimental methods and instrumentation in psychology*, New York: McGraw Hill, 1966.

Bartlett, F. C. Anticipation in human performance. In G. Ekman, T. Husen, G. Johansson, & C. I. Sandstrom (Eds.), *Essays in psychology*, Uppsala: Almquist and Wiksells, 1951.

Battye, C. K., & Joseph, J. An investigation of telemetering of the activity of some muscles in walking. *Medical and Biological Engineering*, 1966, *4*, 125-135.

Beckwith, T. G., & Buck, N. L. *Mechanical measurements*. Reading, Massachusetts: Addison-Wesley, 1961.

Bennett, W. F. Autocorrelation and crosscorrelation analyses of tracking behavior. Doctoral dissertation, Ohio State University, 1957.

Bilodeau, I. Mc. D. Information feedback. In E. A. Bilodeau (Ed.), *Acquisition of skill*. New York: Academic Press, 1966.

Bryan, W. & Harter, N. Studies on the telegraphic language: The acquisition of a hierarchy of habits. *Psychological Review*, 1899, *6*, 345-375.

Burgett, A. L. A study of the variability of human operator performance based on the cross-over model. *Proceedings of the Fifth Annual NASA University Conference on Manual Control*, 1970, NASA SP-215, 11-128.

Crossman, E. R. F. W. A theory of the acquisition of speed-skill. *Ergonomics*, 1959, *2*, 153-166.

Elkind, J. I. *Characteristics of Simple Manual Control*, M.I.T., Lincoln Lab., TR-III, April 1956.

Evarts, E. V. Changing concepts in the central control of movement. *Canadian Journal of Physiology and Pharmacology*, 1975, *53*, 191-201.

Fiske, D. W., & Rice, L. Intra-individual response variability. *Psychological Bulletin*, 1955, *52*, 217-250.

Fitts, P. M., Bennett, W. F., & Bahrick, H. P. Application of autocorrelation and cross-correlation analysis to the study of tracking behavior. In G. Finch & F. Cameron (Eds.), *Air Force human engineering, personnel, and training research.* Baltimore, Maryland: USAF Air Research and Development Command Technical Report 56-8, 1956, 124-141.

Fitts, P. M., Noble, M. R., Bahrick, H. P., & Briggs, G. E. Skilled Performance I and II. *Final Report by Ohio State University Research Foundation to the Wright Air Development Center*, 1959, Project 686.

Fleishman, E. A. A factor analysis of intra-task performance on two psychomotor tests. *Psychometrika*, 1953, *18*, 45-55.

Fuchs, A. H. The progression-regression hypothesis in perceptual-motor skill learning. *Journal of Experimental Psychology*, 1962, *63*, 177-182.

Gaskell, R. E. *Engineering mathematics*. New York: Holt-Dryden, 1958.

Gentile, A. M. A working model of skill acquisition with application to teaching. *Quest*, *18*, 3-23, 1972.

Gentile, A. M., & Nacson, J. Organizational processes in motor control. In J. Keough and R.S. Hutton (Eds.), *Exercise and Sport Sciences Review*, 1976, *4*, 1-33.

Glencross, D. J. Serial organization and timing in a motor skill. *Journal of Motor Behavior*, 1970, *2*(4), 299-237.

Glencross, D. J. Temporal organization in a repetitive speed skill. *Ergonomics*, 1973, *16*, 765-776.

Glencross, D. J. The effects of changes in task conditions on the temporal organization of a repetitive speed skill. *Ergonomics*, 1975, *18*, 17-28.

Glencross, D. J. Output and response processes in sports skills. In D. J. Glencross (Ed.), *Psychology and sport*. Syndey: McGraw-Hill, 1978.

Glencross, D. J. Output and response processes in skilled performance. In G. C. Roberts and K. M. Newell (Eds.), *Psychology of motor behavior and sport -- 1978*. Champaign, Ill.: Human Kinetics Publishers, 1979.

Henry, F. M. Reliability, measurement error, and intra-individual difference. *Research Quarterly*, 1959, *30*, 21-24.

Henry, F. M. Variable and constant performance errors within a group of individuals. *Journal of Motor Behavior*, 1974, *6*, 149-154.

Higgins, J. R., & Spaeth, R. K. Relationship between consistency of movement and environmental conditions. *Quest*, 1972, *17*, 61-69.

Houtz, S. J., & Fischer, F. J. An analysis of muscle action and joint excursion during exercise on a stationary bicycle. *Journal of Bone and Joint Surgery*, 1959, 41-A, 123-131.

Jones, M. B. Practice as a process of simplification. *Psychological Review*, 1962, *69*, 274-294.

Jones, M. B. A two-person theory of individual differences in motor learning. *Psychological Review*, 1970, *77*(4), 353-360.

Keele, S. W. Movement control in skilled motor performance. *Psychological Bulletin*, 1968, *70*, 387-403.

Kelley, Y. C. *Manual and Automatic Control: A theory of manual control and its application to manual and to automatic systems.* New York: John Wiley and Sons, 1968.

Lathrop, R. G. Some principles for development of new measures of human continuous performance. *Perceptual and Motor Skills*, 1965, *20*, 453-458.

Lewis, R. E. F. Consistency and car driving skill. *British Journal of Industrial Medicine*, 1956, *13*, 131-141.

Lindahl, L. G. Movement analysis as an industrial training method. *Journal of Applied Psychology*, 1945, *29*, 420-436.

Lundervold, A. Electromyographic investigations during typewriting. *Ergonomics*, 1958, *1*, 226-233.

Magdaleno, R. E., Jex, H. R., & Johnson, W. A. Tracking quasi-predictable displays: Subjective predictability gradations, pilot models for periodic and narrow band inputs. *Proceedings of the Fifth Annual NASA-University Conference on Manual Contol*, 1970, NASA SP-215, 391-428.

Marteniuk, R. G. Individual differences in intra-individual variability. *Journal of Motor Behavior*, 1969, *1*, 309-318.

Marteniuk, R. G., & MacKenzie, C. L. Information processing in movement organization and execution. Paper presented at Attention and Performance VIII, Princetown, New Jersey, August 1978.

Miller, G., Galanter, E., & Pribram, K. *Plans and the Structure of Behavior*. New York: Holt, 1960.

Neisser, U. *Cognition and reality*. San Francisco: Freeman, 1976.

Noble, N. & Trumbo, D. The Organization of Skilled Response. *Organizational Behavior and Human Performance*, 1967, *2*, 1-25.

Noble, N., Trumbo, D., Ulrich, L., & Cross, K. Task Predictability and the Development of Tracking Skill under Extended Practice. *Journal of Experimental Psychology*, 1966, *72*, 85-99.

Norrie, M. L. Practice effects on reaction latency for simple and complex movements. *Research Quarterly*, 1967, *38*, 79-85.

Person, R. S. An electromyographic investigation on co-ordination of the activity of antagonist muscles in man during the development of a motor habit. *Pavlovian Journal of Higher Nervous Activity*, 1958, *8*, 13-23.

Pew, R. W. Acquisition of hierarchical control over the temporal organization of a skill. *Journal of Experimental Psychology*, 1966, *71*, 764-771.

Pew, R. W. Human-perceptual-motor performance. In B. Kantowitz (Ed.), *Human information processing: Tutorials in performance and cognition*. Potomac, Md.: LEA publishing, 1974(a).

Pew, R. W. Levels of analysis in motor control. *Brain Research*, 1974, *71*, 393-400, (b).

Pew, R. & Rupp, G. L. Two quantitative measures of skill development. *Journal of Experimental Psychology*, 1971, *90*, 1-7.

Poulton, E. C. The basis of perceptual anticipation in tracking. *British Journal of Psychology*, 1952, *43*, 295-302.

Poulton, E. C. On prediction in skilled movement. *Psychological Bulletin*, 1957, *54*, 467-478.

Poulton, E. C. *Tracking skill and manual control*. New York: Academic Press, 1974.

Poulton, E. C. Range effects and asymmetric transfer in studies of motor skill. Paper presented at the International Congress in Physical Education, Trois Rivieres, 1979.

Reynolds, B. Correlation between two psychomotor tasks as a function of distribution of practice on the first. *Journal of Experimental Psychology*, 1952, *43*, 341-348.

Schmidt, R. A. A schema theory of discrete motor skill learning. *Psychological Review*, 1975, *82*, 225-260.

Schmidt, R. A., Zelaznik, H., Hawkins, B., Frank, J. S., & Quinn, J. T., Jr. Motor-output variability: A theory for the accuracy of rapid motor acts. *Psychological Review*, 1979, *86*, 415-451.

Seashore, R. H., & Bavelas, A. The functioning of knowledge of results in Thorndike's line drawing experiment. *Psychological Review*, 1941, *48*, 155-164.

Shaffer, L. H. Timing in the motor programming of typing. *Quarterly Journal of Experimental Psychology*, 1978, *30*, 333-345.

Slack, C. W. Learning in simple one-dimensional tracking. *American Journal of Psychology*, 1953, *66*, 33-44.

Slater-Hammel, A. T. Action current study of contraction-movement relationships in golf stroke. *Research Quarterly*, 1948, *19*, 164-177.

Summers, J. J. The role of timing in motor program representation. *Journal of Motor Behavior*, 1975, *7*, 229-241.

Summers, J. J. The relationship between the sequencing and timing components of a skill. *Journal of Motor Behavior*, 1977, *9*, 49-59.

Thorndike, E. L. *Human Learning*. Century (Reprinted 1966, M. I. T. Press), 1931.

Tyldesley, D. A., & Whiting, H. T. A. Operational timing. *Journal of Human Movement Studies*, 1975, *1*, 172-177.

Turvey, M. T. Preliminaries to a theory of action with reference to vision. In R. Shaw & J. Bransford (Eds.), *Perceiving, acting, and knowing: Toward an ecological psychology*. Hillsdale, N. J.: Erlbaum, 1977.

Vossius, G. Der kybernetische aspekt der willkurbewegung. *Progress in Cybernetics*. New York: Elsevier Publishing Co., 1965.

Welch, M., & Henry, F. M. Individual differences in various parameters of motor learning. *Journal of Motor Behavior*, 1971, *3*(1), 78-96.

Wing, A. & Kristofferson, A. B. Response delays and the timing of discrete motor responses. *Perception and Psychophysics*, 1973, *14*, 5-12.

Zohar, D. Amount and order of redundancy as determinants of continuous tracking performance. *Journal of Motor Behavior*, 1974, *6*(3), 165-178.

APPENDICES

Appendix A

Tracking Task

A tracking task was chosen to serve as the vehicle from which continuous analysis of skilled performance can be obtained. The pursuit tracking task has been recommended as a task for study in the laboratory by many authors. Poulton (1957) has outlined three reasons for its use as an experimental tool.

(1) The target movement can be varied along psychological dimensions from simple and repetitive to more complex and irregular.

(2) The frequency and amplitude of the stimulus course can be varied.

(3) Both input and output can be recorded simultaneously.

In his view of tracking behaviour, Adams (1961) also addresses the advantages of tracking tasks.

> Tracking studies typically use more elaborate apparatus which allows for controlled manipulation of such variables as the function of the input signal, scale factors, mathematical transformations of the output signal, characteristics of the control mechanisms, etc. . . . (p. 55).

The classification of stimulus signals from tracking studies has been illustrated by Fitts, Noble, Bahrick, and Briggs (1959). Discrete and continuous stimulus signals are classified in the following manner.

(1) Periodic. Signals that can be specified exactly as a mathematical process and that exhibit periodicity, e.g., sine waves.

(2) Aperiodic. Signals that can be specified exactly as a mathematical process and that do not exhibit periodicity, e.g., constant velocity course.

(3) Random. Signals having characteristics that can be specified as stationary statistical functions, e.g., electrical noise.

(4) Quasi-random. Signals that cannot be generated by stationary statistical processes, e.g., signals generated from arbitrarily chosen cam counters.

Within these classifications it is possible to utilize stimulus complexity and frequency characteristics to predict the difficulty and similarity of a serially organized tracking task. These characteristics enable the experimenter to specify the degree of coherency[†] the subject is exposed to during continuous tracking behaviour. Furthermore, the operators decision to make a series of rapid aiming movements involves prediction. This predictive behaviour, that is part of a simple learning process (Poulton, 1952), allows the researcher the opportunity to investigate the underlying processes involved in the acquisition of a motor task.

From the research that has been reviewed, it would appear that tracking would be a useful task with which to investigate the acquisition and subsequent retention of a motor task.

[†] Coherency is defined as the abstraction of patterns in predictable functions.

Appendix B

Intra-individual variability

The total variability in motor performance within a group of individuals can be fractionated into individual differences (true score variance), variability within the individual from trial to trial (intra-individual variance), and instrumental and observational errors (error variance).[†] In an extensive review of response variability, Fiske and Rice (1955) define three types of intra-individual variability. Pure intra-individual variability (type I) is defined as

> ... the difference between two responses of an individual at two points in time under the following conditions: (a) the individual is exposed each time to the same stimulus or to objectively indistinguishable stimuli; (b) the total situation in which the responses are made is the same on both occasions (p. 217).

The assumptions of the first type of intra-individual variability are that (1) the order of the responses is not stated, (2) the responses show no trend over time (e.g., fatigue, learning, etc.), and (3) this response variability is not random. Type II or reactive variability has one additional limitation to that of Type I. That is, responses show some pattern or order, and are not just a monotonic function of time. Finally, Type III differs from pure intra-individual variability in that different stimuli are presented on the two occasions. The adaptability of the subject to respond to changing stimuli is of importance. The above definitions, while providing a guiding framework, are not intended as mutually exclusive categories. Modifications to, or part combinations of, different types are possible. When the experimental concern is that of learning over repeated trials, a combination of Type I and Type II is needed to operationally define the intra-individual variability being used.

[†] The majority of the research carried out under Franklin Henry at Berkeley was concerned with the recognition of this fractionation (Henry, 1959; Marteniuk, 1969; Welch and Henry, 1971).

Appendix C

Superdiagonal Form of Correlation Matrices

Certain correlations among trials of practice almost always form themselves into a "superdiagonal form".

> The correlations are largest in the superdiagonal, between neighboring trials, and decrease going up the columns or across the rows to the right with smallest correlations in the upper-right-hand corner of the matrix (Jones, 1970; p. 353).

This finding has been confirmed by many authors, notably, Adams (1953), Fleishman (1953), Jones (1962) and Reynolds (1952).

This superdiagonal form is an ordinal regularity and takes the form of inequalities.

$$\gamma_{ij} > \gamma_{ik}$$

and

$$\gamma_{jk} > \gamma_{ik}$$

where practice trials i, j and k are completed in alphabetic order. Although this does not specify an exact rule, correlations among trials of practice have been shown to follow an exact regularity, namely the *single-tetrad rule*. This rule requires that $\gamma_{ik}.\gamma_{jl} = \gamma_{il}.\gamma_{jk}(i<j<k<l)$.

Superdiagonal form and the single tetrad rule are general in matrices of intertrial correlations. However during certain tasks the superdiagonal pattern is present early in practice and then later in practice the remote correlations approach zero. Using a simple motor task as an example (micrometer adjustment) Jones (1970) relates this wasting away of the superdiagnoal form to the fact that all subjects terminate at close to the same level of proficiency, and that this terminal efficiency asymptotes before the end of the practice trials. Early in practice, there are reliable differences between subjects, these differences structure the superdiagonal form. This form gets progressively weaker as the subjects approach nearer and nearer perfection on the task. This process is termed as pure *rule process*. It reflects differences in the routes different subjects go about mastering the task in different ways. The rate process can be defined separately from the terminal process. The terminal process being the method by which subjects stabilize at different terminal levels. Both rate and terminal processes are the basis of Jones' "Two Process Theory of Individual Differences in Motor Learning".

> Intertrial correlations should be understood in terms of a terminal process defined by levels of proficiency after indefinite amounts of practice in the routes by which different subjects arrive at their terminal positions (p. 356).

Examining the total correlation matrix of practice trials, it is suggested that the terminal process contributes less to the correlations early on in practice while the rate process predominates. Therefore early in practice the correlations should increase along rows to the left. These differences from one column to the next are great due to greater individual differences. However later in practice the rate process loses its effect while the terminal process increases in strength. The differential steps from one trial to the next are now quite small and may be increasing to the right along the rows.

Jones concludes his description of his learning theory by stating the following.

> Differential processes are an integral part of learning. They take place in the same people, on the same task, at the same time. And any experimental study which ignores them is incomplete (Jones, 1970; p. 360).

APPENDIX D

Table D1 (Expt. IV)

Within Block Correlations of Movement Velocities for Subject 1 (D.S.) during Blocks 1, 5 and 10.

TRIAL	1	2	3	4	5	6	7
Block 1							
1	---	.66	.72	.83	.79	.87	.75
2		---	.97	.57	.88	.69	.78
3			---	.72	.95	.75	.87
4				---	.81	.91	.90
5					---	.83	.93
6						---	.86
7							---
Block 5							
1	---	.92	.82	.92	.84	.91	.89
2		---	.89	.95	.81	.92	.91
3			---	.90	.85	.88	.91
4				---	.87	.96	.90
5					---	.85	.75
6						---	.89
7							---
Block 10							
1	---	.94	.87	.87	.90	.76	.81
2		---	.92	.91	.94	.82	.86
3			---	.96	.94	.87	.86
4				---	.95	.88	.87
5					---	.91	.95
6						---	.96
7							---

Table D2 (Expt. IV)

Within Block Correlations of Movement Velocities for Subject 2 (B.G.) during Blocks 1, 5 and 10.

Trial	1	2	3	4	5	6	7
Block 1							
1	---	.89	.73	.64	.79	.71	.73
2		---	.78	.70	.83	.71	.65
3			---	.86	.88	.68	.36
4				---	.85	.70	.34
5					---	.64	.34
6						---	.73
7							---
Block 5							
1	---	.75	.76	.76	.66	.71	.61
2		---	.92	.93	.90	.93	.93
3			---	.84	.88	.90	.91
4				---	.91	.92	.81
5					---	.94	.86
6						---	.87
7							---
Block 10							
1	---	.92	.96	.94	.91	.85	.95
2		---	.92	.95	.98	.71	.89
3			---	.94	.90	.86	.94
4				---	.95	.78	.95
5					---	.73	.89
6						---	.90
7							---

Table D3 (Expt. IV)

Within Block Correlations of Movement Velocities for Subject 3 (T.W.) during Blocks 1, 5 and 10.

Trial	1	2	3	4	5	6	7
Block 1							
1	---	.79	.56	.71	.73	.45	.72
2		---	.64	.79	.90	.63	.89
3			---	.77	.77	.90	.85
4				---	.81	.82	.87
5					---	.73	.94
6						---	.83
7							---
Block 5							
1	---	.91	.86	.86	.97	.83	.86
2		---	.95	.86	.90	.93	.98
3			---	.78	.84	.90	.95
4				---	.88	.87	.82
5					---	.82	.86
6						---	.93
7							---
Block 10							
1	---	.93	.93	.95	.95	.97	.95
2		---	.91	.91	.96	.95	.95
3			---	.89	.91	.90	.88
4				---	.92	.95	.96
5					---	.94	.91
6						---	.97
7							---

Table D4 (Expt. IV)

Within Block Correlations of Movement Velocities

for Subject 4 (I.H.) during Blocks 1, 5 and 10.

Trial	1	2	3	4	5	6	7
Block 1							
1	---	.76	.82	.87	.61	.90	.70
2		---	.77	.77	.80	.67	.80
3			---	.82	.74	.78	.88
4				---	.64	.76	.77
5					---	.57	.82
6						---	.71
7							---
Block 5							
1	---	.88	.92	.83	.83	.93	.92
2		---	.84	.90	.88	.83	.81
3			---	.89	.90	.96	.95
4				---	.96	.89	.86
5					---	.89	.85
6						---	.96
7							---
Block 10							
1	---	.89	.89	.94	.89	.89	.89
2		---	.92	.96	.96	.92	.95
3			---	.91	.92	.94	.95
4				---	.92	.93	.93
5					---	.94	.98
6						---	.97
7							---

Table D5 (Expt. IV)

Within Block Correlations of Movement Velocities for Subject 5 (J.S.) during Blocks 1, 5 and 10.

Trial	1	2	3	4	5	6	7
Block 1							
1	---	.89	.86	.82	.50	.75	.75
2		---	.85	.85	.39	.81	.85
3			---	.89	.72	.95	.87
4				---	.66	.91	.90
5					---	.76	.58
6						---	.89
7							---
Block 5							
1	---	.84	.93	.86	.91	.85	.85
2		---	.83	.91	.84	.93	.72
3			---	.89	.92	.88	.90
4				---	.87	.98	.73
5					---	.87	.89
6						---	.77
7							---
Block 10							
1	---	.91	.88	.87	.95	.95	.96
2		---	.95	.96	.94	.93	.95
3			---	.94	.93	.93	.90
4				---	.92	.92	.92
5					---	.97	.96
6						---	.96
7							---

APPENDIX E

Table El (Expt. IV)

Mean, Standard Deviation and Correlation Matrix for the RMSEt of each Block of Trials.

Subject 1 (D.S.)

Block	Mean	SD
1	80	38
2	66	33
3	62	37
4	56	28
5	50	28
6	46	24
7	37	12
8	41	19
9	45	22
10	37	22

Block	1	2	3	4	5	6	7	8	9	10
1	---	.73	.87	.87	.79	.56	.42	.48	.60	.61
2		---	.85	.79	.68	.61	.46	.60	.69	.81
3			---	.94	.88	.73	.53	.70	.77	.80
4				---	.87	.69	.54	.69	.74	.76
5					---	.69	.65	.63	.65	.67
6						---	.64	.85	.86	.75
7							---	.80	.72	.77
8								---	.92	.91
9									---	.87
10										---

Table E2 (Expt. IV)

Mean, Standard Deviation and Correlation Matrix

for the RMSEt of each Block of Trials.

Subject 2 (B.G.)

Block	Mean	SD
1	98	46
2	55	36
3	54	26
4	68	38
5	57	26
6	53	22
7	53	31
8	57	35
9	44	30
10	46	27

Block	1	2	3	4	5	6	7	8	9	10
1	---	.82	.90	.77	.80	.48	.35	.48	.55	.56
2		---	.81	.95	.90	.65	.68	.84	.87	.84
3			---	.76	.84	.48	.28	.47	.56	.55
4				---	.93	.62	.75	.88	.87	.88
5					---	.60	.66	.78	.84	.81
6						---	.63	.61	.72	.51
7							---	.93	.89	.86
8								---	.95	.94
9									---	.90
10										---

Table E3 (Expt. IV)

Mean, Standard Deviation and Correlation Matrix for the RMSEt of each Block of Trials.

Subject 3 (T.W.)

Block	Mean	SD
1	82	39
2	54	26
3	40	18
4	45	26
5	40	24
6	40	14
7	32	12
8	31	17
9	38	17
10	33	17

Block	1	2	3	4	5	6	7	8	9	10
1	---	.69	.71	.58	.60	.63	.61	.57	.52	.63
2		---	.56	.30	.26	.58	.31	.13	.22	.41
3			---	.71	.73	.63	.63	.63	.58	.61
4				---	.93	.73	.74	.86	.85	.79
5					---	.67	.72	.88	.76	.73
6						---	.83	.75	.80	.88
7							---	.87	.81	.92
8								---	.91	.86
9									---	.88
10										---

Table E4 (Expt. IV)

Mean, Standard Deviation and Correlation Matrix for the RMSEt of each Block of Trials.

Subject 4 (I.H.)

Block	Mean	SD
1	67	35
2	49	24
3	37	21
4	43	27
5	31	15
6	36	11
7	36	19
8	34	20
9	35	19
10	34	22

Block	1	2	3	4	5	6	7	8	9	10
1	---	.75	.81	.83	.69	.49	.85	.70	.84	.68
2		---	.90	.85	.85	.46	.77	.74	.84	.67
3			---	.92	.89	.61	.90	.81	.89	.73
4				---	.87	.48	.89	.89	.90	.71
5					---	.63	.87	.90	.91	.82
6						---	.65	.57	.61	.69
7							---	.83	.94	.86
8								---	.89	.81
9									---	.90
10										---

Table E5 (Expt. IV)

Mean, Standard Deviation and Correlation Matrix for the RMSEt of each Block of Trials.

Subject 5 (J.S.)

Block	Mean	SD
1	75	39
2	64	34
3	64	24
4	47	22
5	43	22
6	44	24
7	41	26
8	41	21
9	38	23
10	36	20

Block	1	2	3	4	5	6	7	8	9	10
1	---	.85	.38	.57	.79	.76	.81	.76	.80	.75
2		---	.62	.76	.82	.82	.91	.80	.82	.71
3			---	.60	.43	.46	.50	.45	.38	.20
4				---	.86	.82	.83	.80	.76	.62
5					---	.93	.92	.93	.91	.87
6						---	.92	.93	.88	.88
7							---	.93	.93	.82
8								---	.96	.89
9									---	.87
10										---